History of Synchrotron Radiation Sources

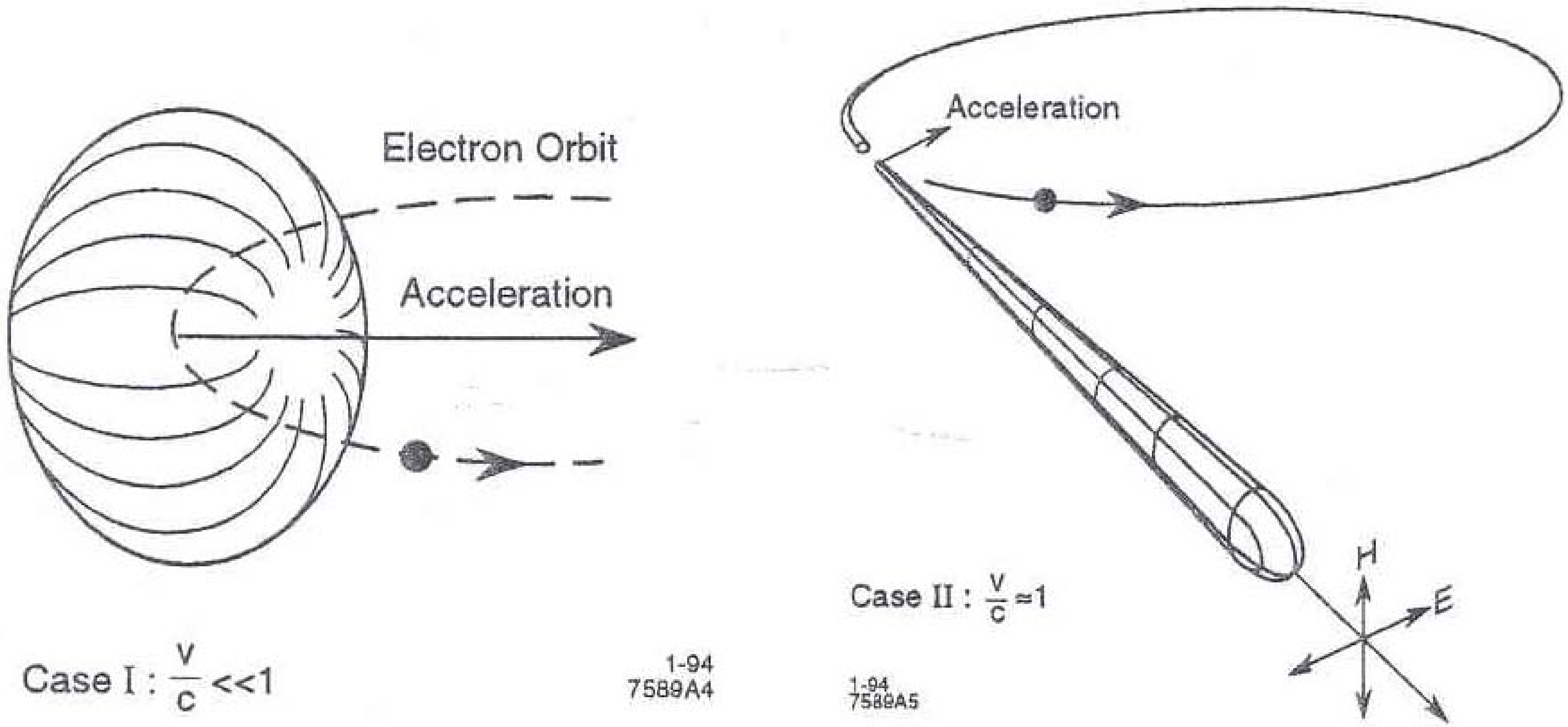
R. Hettel, SSRL

NGC 1952
(Crab Nebula)

- supernova (1054)
- remnant discovered 1731 (John Bevis)
- bluish background proposed to be SR in 1953 by J. Shklovsky

- History of SR development
- 1st generation SR sources
- 2nd generation SR sources
- SR experimentation
- Beam stabilizing systems
- SR flux and brightness
- 3rd generation sources
- Improving 3rd generation sources
- 4th gen demands and options
- Stability requirement preview

Synchrotron Radiation



Synchrotron Radiation Discovery

from A. L. Robinson, X-ray Data Booklet, LBL

1897: Larmor derived total power radiated by classical accelerated charged particle:

$$P(MKS) = \frac{a^2(t')q^2}{6\pi\varepsilon_0 c^3}$$

q = charge
a = acceleration
t′ = t - r/c = retarded time

1898: Lienard derived power from relativistic particle accelerated in circle:

$$P \propto \frac{(E/m_0c^2)^4}{R^2} = \frac{\gamma^4}{R^2}$$

m_0 = rest mass
R = radius of circular orbit

1907: Schott obtained expressions for the angular distribution of the radiation from as function of orbital frequency of electron circling in magnetic field

Synchrotron Radiation Discovery – cont.

1920s: Concepts for magnetic induction electron accelerators (betatrons) to produce x-rays from fixed target

1940: Kerst builds first 2.3-MeV betatron at University of Illinois. Followed by 20-MeV and 100-MeV machines by GE

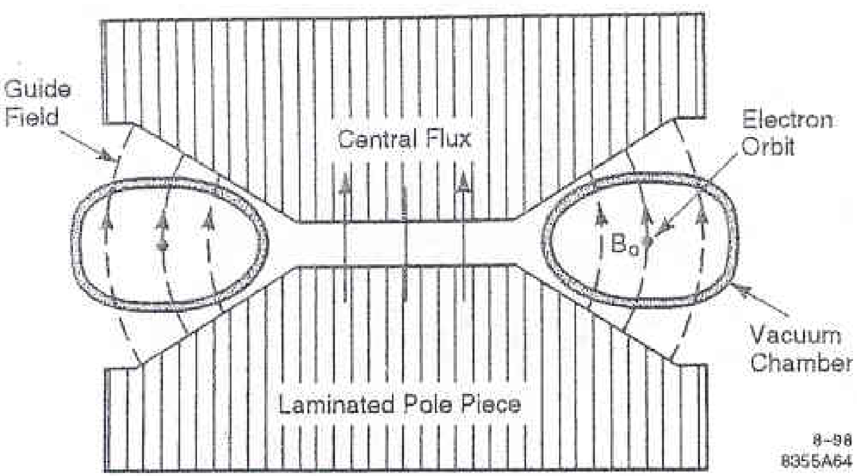


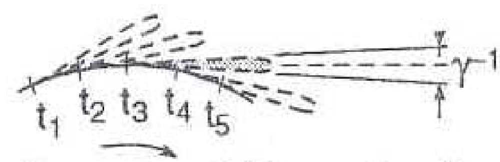
Figure 1: Betatron schematic.

1944: Ivanenko and Pomerchank show that energy losses from radiating electrons would set limit on maximum betatron energy (500 MeV)

Synchrotron Radiation Discovery – cont.

mid-40s: Schwinger derives properties of relativistic particles accelerated in a circle:

- forward-peaked distribution ("searchlight"):

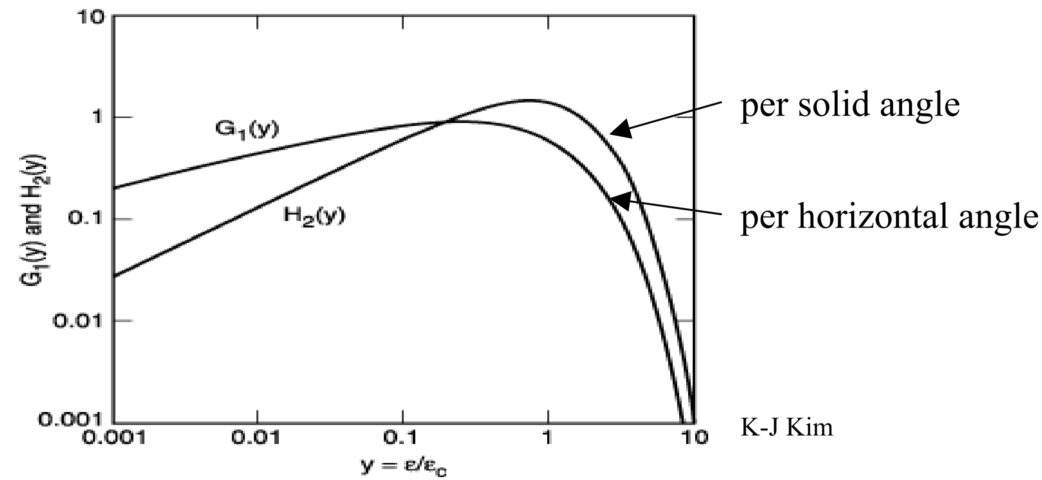


opening angle: $\sigma'_{\Psi} \sim 1/\gamma = \sim 0.5\,\mathrm{mrad}$ **for 1 GeV electrons**

- photon energy peak $\propto E^3/R$

critical energy: $E_{crit} = 3\hbar c\gamma^3 / 2\rho = \sim 1\ \mathrm{keV}$ **for 1 GeV ring**

- spectral distribution:



K-J Kim

- polarization:

horizontally polarized in ring plane
elliptically polarized above and below ring plane

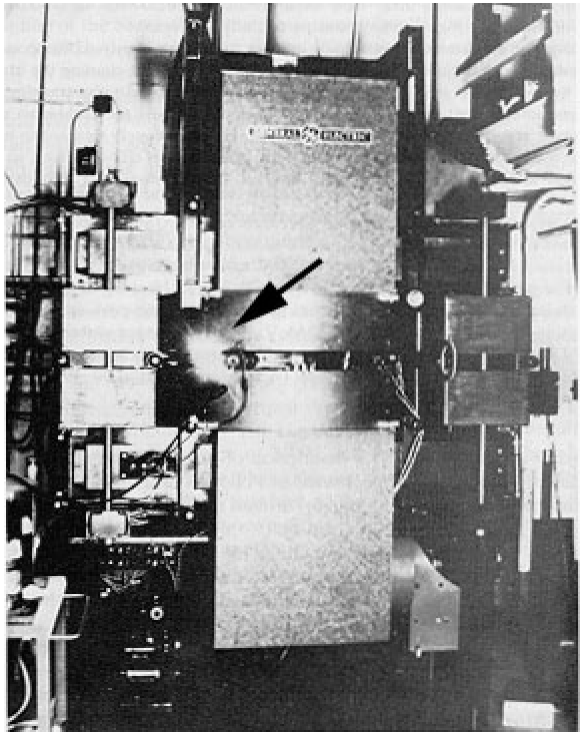
Synchrotron Radiation Discovery – cont.

1945: McMillan (US) and Veksler (USSR) independently propose synchro-cyclotron to reach higher energies:

as particle energy increases, mass increases, time-of-arrival at rf accelerating gap is retarded

reduce rf frequency with increasing energy to maintain synchronization

beams are stably bunched ("synchrotron" oscillations about equilibrium)



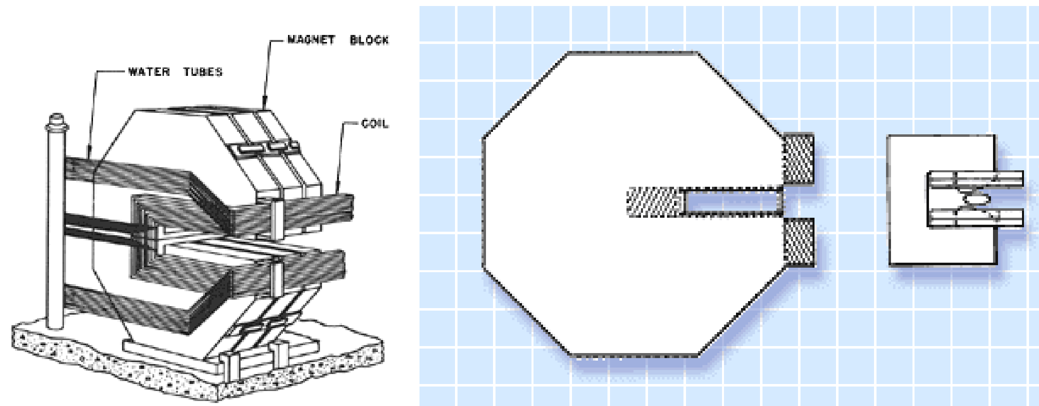
1947: Pollack builds 70-MeV synchro-cyclotron at GE, having transparent tube to observe HV sparking; instead, a bright arc of light from electrons is seen

Langmuir identifies light as "Schwinger radiation" (synchrotron radiation)

Synchrotron Radiation Discovery – cont.

1950s: Courant, Livingston, Snyder (Brookhaven) discover alternating gradient, strong focusing principle that enables high energy machines to be built. First design is 1.3 GeV electron ring at Cornell (1954)

Proton Cosmotron at BNL



3.3 GeV Cosmotron magnet vs. 33 GeV AGS magnet

from http://www.bnl.gov/bnlweb/history/focusing.html

1956: First soft x-ray spectroscopy experiments by Tomboulian and Hartman at Cornell (320 MeV)

1st Generation Synchrotron Radiation Sources
-parasitic operation-

~1961: SURF, 180-MeV electron synchrotron UV source at NBS

1.1-GeV electron synchrotron at Frascati

Frascati synchrotron

1962: First multi-GeV electron synchrotron to produce x-rays (3 GeV CEA) (1st wiggler 1966)

mid-60s: 750-MeV SOR (synchrotron orbital radiation) in Tokyo

6-GeV DESY synchrotron (100 keV x-rays)

1st Generation Storage Ring SR Sources
-parasitic operation-

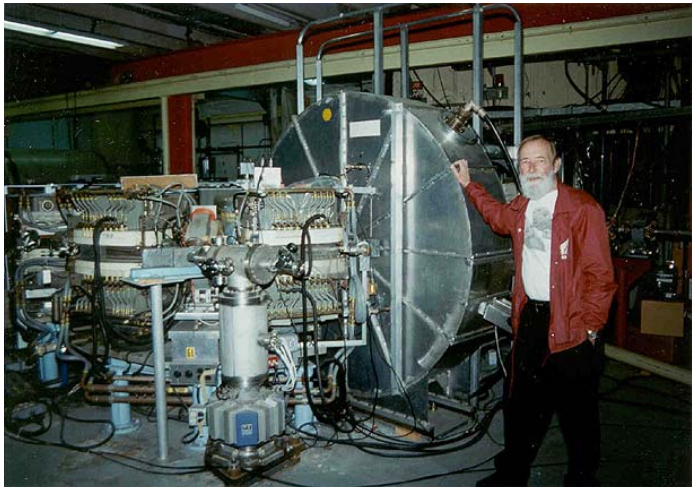
1967: 240-MeV Tantalus I electron storage ring in Wisconsin
1971: 540-MeV ACO ring in Orsay

1974: 240-MeV SURF II for NBS

300-MeV SOR ring in Tokyo
(1st ring designed for SR)

1st x-ray beam line on 2.5-GeV SPEAR

mid-70s:
2-GeV VEPP-3 at INP in Novosibirsk
1.9 GeV DCI at Orsay
4.5-GeV DORIS at DESY
4.5-GeV SPEAR
6-GeV CESR (CHESS)



Ed Rowe and Tantalus 1

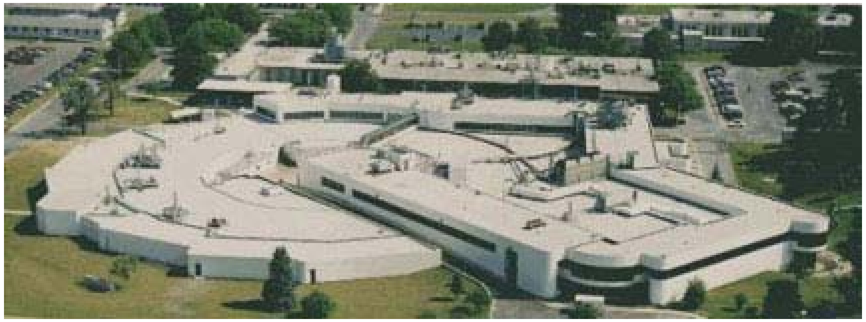
Note: large emittance (~500 nm-rad) for colliding beams

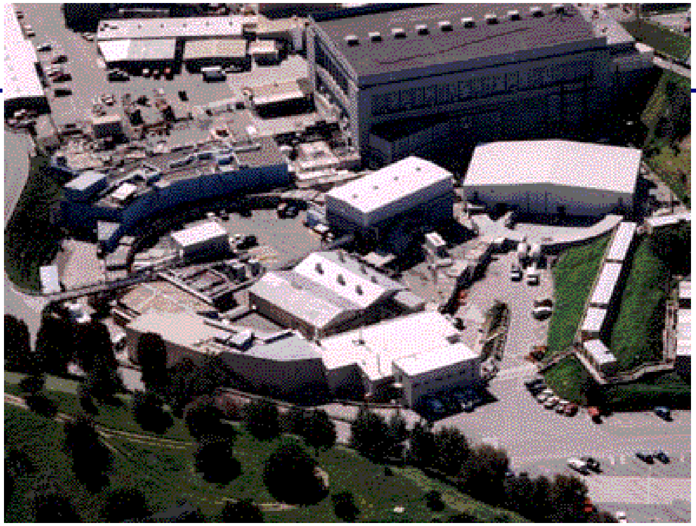
2nd Generation Storage Ring SR Sources

-dedicated for SR-

1981:	2-GeV SRS at Daresbury	(ε = 106 nm-rad)
	HASYLAB established at DORIS, DESY	(ε = 430 nm-rad)
1982:	700-MeV VUV ring at NSLS	(ε = 140 nm-rad)
	800-MeV BESSY in BERLIN	(ε = 38 nm-rad)
	800-MeV NSRL, Hefei	
1983:	2.5-GeV Photon Factory in Japan	(ε = 130 nm-rad)
1984:	2.5 GeV x-ray ring at NSLS	(ε = 102 nm-rad)
	800-MeV SuperACO at LURE, Orsay	(ε = 130 nm-rad)
1985:	550-MeV MAX-lab, Lund	(ε = 100 nm-rad)
	1-GeV Aladdin at Wisconsin	(ε = 130 nm-rad)
1990:	SPEAR 2 becomes dedicated light source for SSRL	(ε = 160 nm-rad)

2nd Generation SR Facilities


NSLS


SSRL (SPEAR 2)

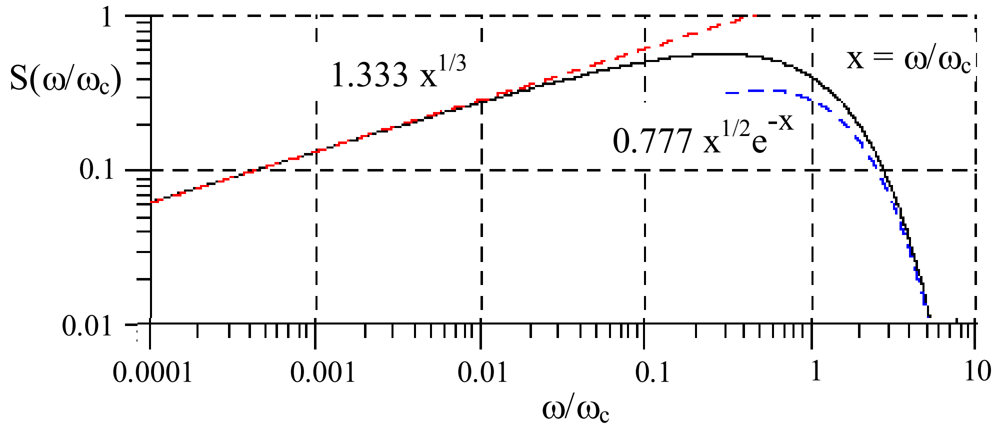

NSRL, Hefei

NSRL, Hefei

2^{nd} Generation Storage Ring SR Sources

-beam characteristics-

Spectral distribution:

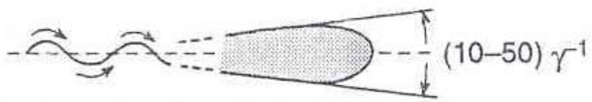


Medium emittance:

$\sigma = (\beta\varepsilon)^{1/2} \Rightarrow \sigma_x \sim 1$ mm $\qquad \sigma_y \sim 0.05\text{-}0.1$ mm

$\sigma' = (\varepsilon/\beta)^{1/2} \Rightarrow \sigma_x' \sim 0.1$ mrad $\qquad \sigma_y' \sim 0.03$ mrad

$(\eta = 0, \alpha_1 = 0)$



Wiggler — Incoherent Superposition

BUT: - horizontal photon opening angle dominated by electron arc in dipoles and wigglers (mrads)

- vertical photon opening angle dominated by $1/\gamma$ (0.5 mrad @ 1GeV)

High flux: $\sim 10^{13}$ photons/s/mrad for 3 GeV, 100 mA dipole source at E_{crit}

SR Experimentation – History of X-rays

from A. L. Robinson, X-ray Data Booklet, LBL

1895: X-rays discovered by Wilhelm Roentgen (Nobel Prize 1901)

1909: Barkla and Sadler discover characteristic x-ray radiation
(1917 Nobel Prize to Barkla)

1912: von Laue, Friedrich, and Knipping observe x-ray diffraction
(1914 Nobel Prize to von Laue)

1913: Bragg, father and son, build an x-ray spectrometer
(1915 Nobel Prize)

1913: Moseley develops quantitative x-ray spectroscopy and Moseley's Law
(frequency of x-ray fluorescence emission from element $\propto Z^2$, Z = atomic number)

1916: Siegbahn and Stenstrom observe emission satellites
(1924 Nobel Prize to Siegbahn)

1921: Wentzel observes two-electron excitations

1922: Meitner discovers Auger electrons

1924: Lindh and Lundquist resolve chemical shifts

1927: Coster and Druyvesteyn observe valence-core multiplets

1931: Johann develops bent-crystal spectroscopy

SR Experimentation

Disciplines (partial list):

- Materials science, complex materials
- Environmental science
- Biology, structural molecular biology
- Biophysics, bioengineering
- Macromolecular, protein crystallography
- Nanotechnology
- Atomic and molecular physics
- Chemical dynamics
- Photochemistry
- Semiconductors
- Lithography
- Surface science
- Magnetism, magnetic materials
- Infrared science
- Femtosecond phenomena
- High pressure science
- Optics

SR Experimentation - cont.

Methods (partial list):

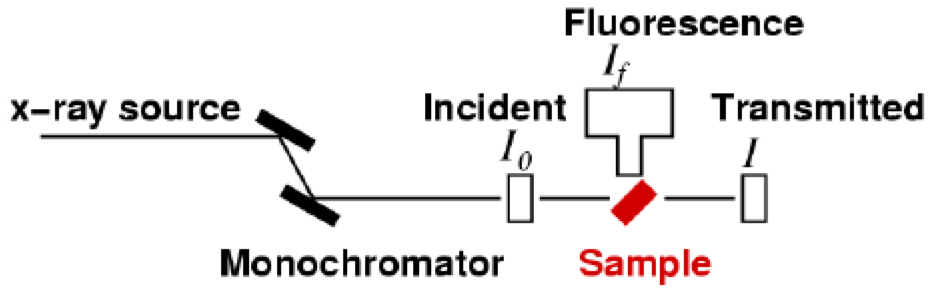
- X-ray absorption spectroscopy (XAS, XAFS, NEXAFS)

X-ray absorption fine structure, near edge XAFS

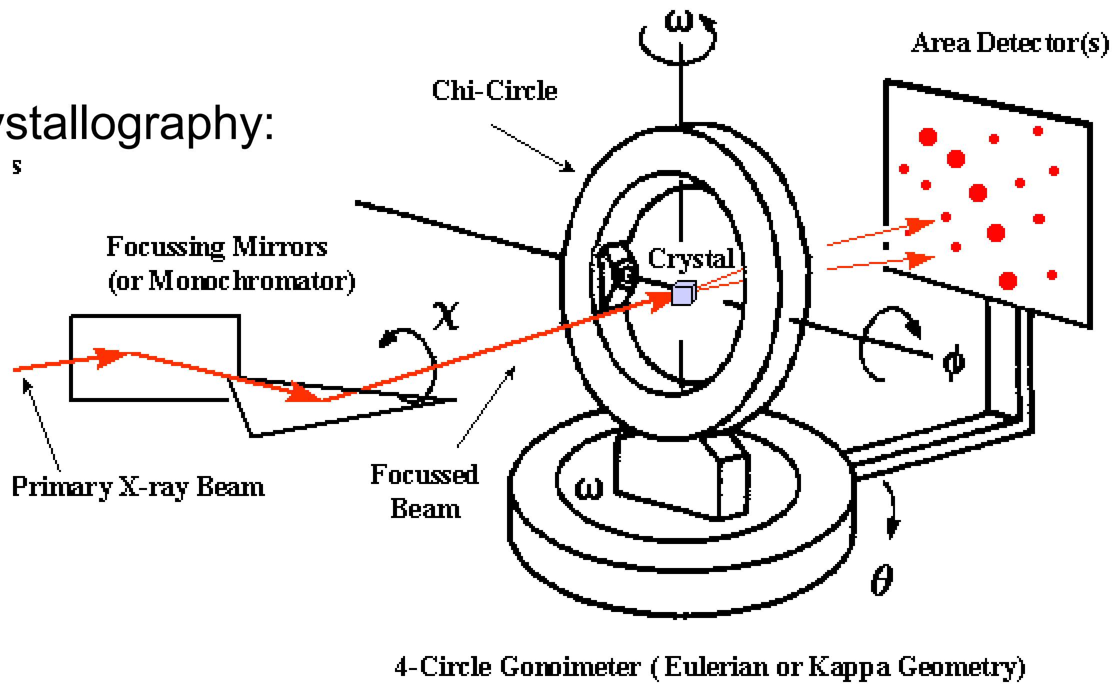
- X-ray anomalous scattering, small angle scattering (SAXS), diffraction anomalous fine structure (DAFS)
- Laue diffraction
- Multiple-wavelength anomalous diffraction (MAD)
- Powder diffraction
- Protein, macromolecular crystallography
- X-ray fluorescence
- X-ray microscopy, microdiffraction
- Magnetic spectroscopy, dichroism, microscopy, spectromicroscopy
- Visible and IR Fourier transform spectroscopy
- IR spectromicroscopy
- Deep-etch x-ray lithography (LIGA)
- Photo-electron, photo-ionization spectroscopy
- Tomography
- Diamond anvil cell
- X-ray intensity interferometry
- X-ray holography, speckle
- Coherent scattering phase retrieval

SR Beam Lines

XAFS:



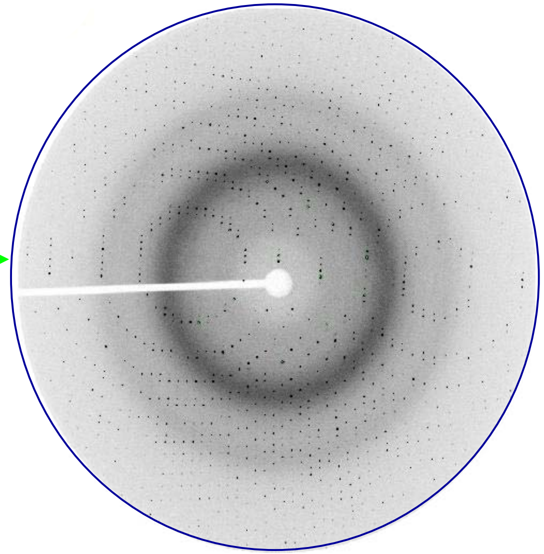
Protein crystallography:



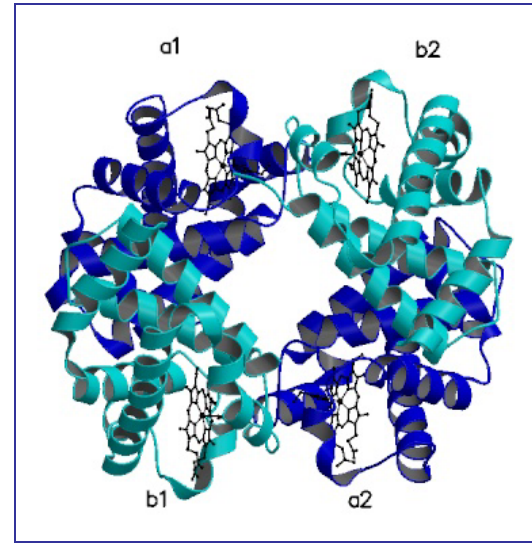
Steps in Crystallography

M. Soltis, SSRL

X Rays

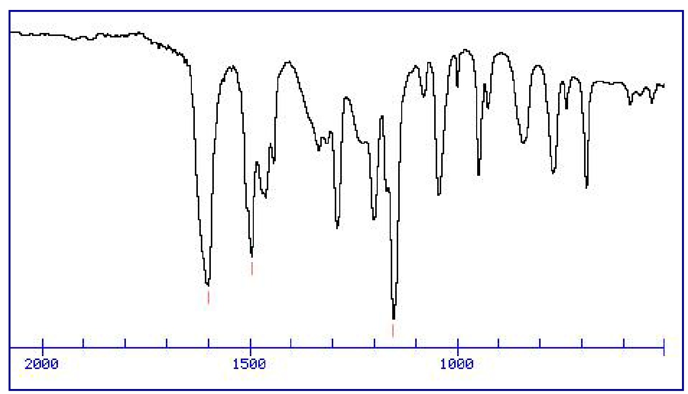


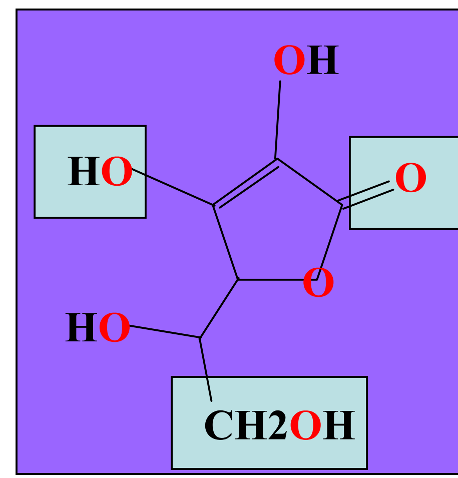
Data Analysis



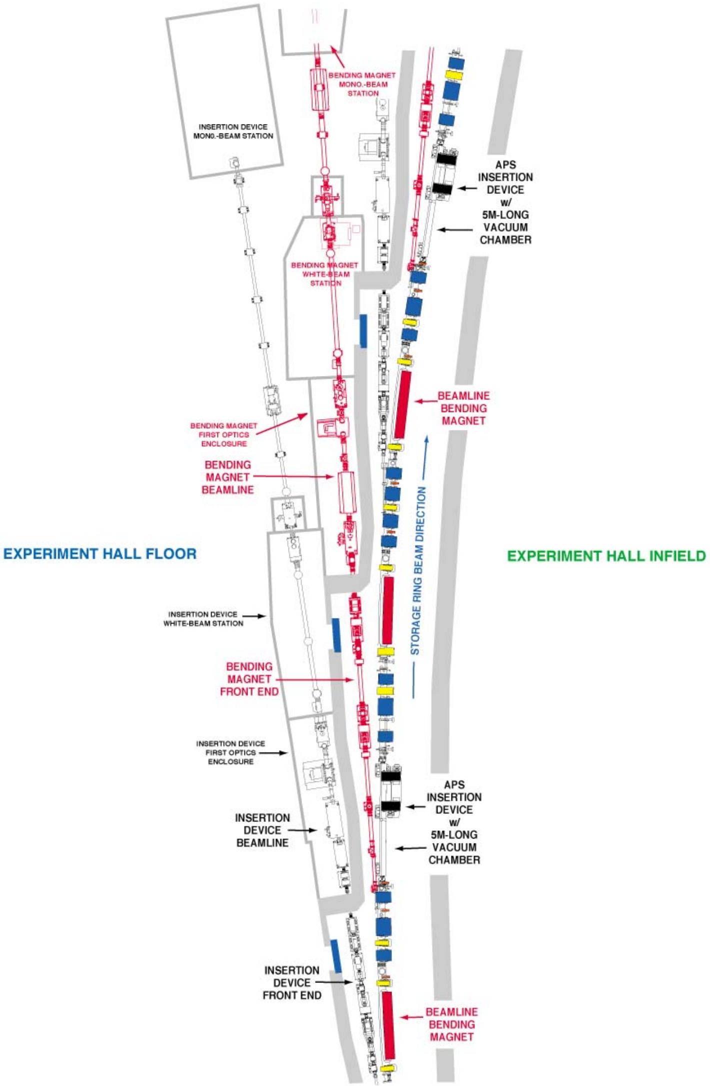
- The wavelength of the light must match the dimensions of the object studied

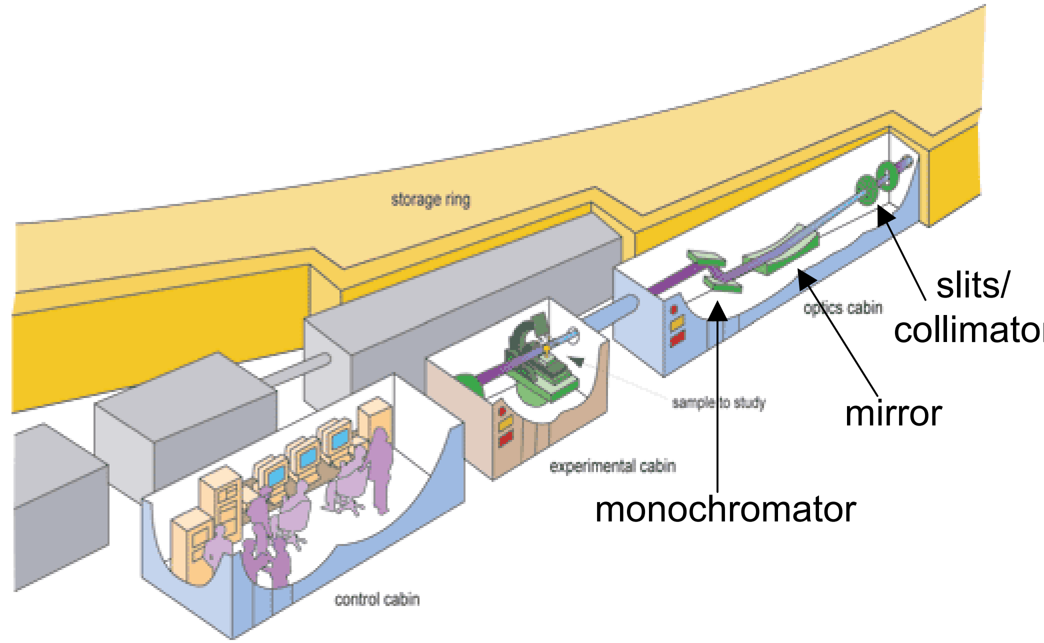
- X-rays with wavelength around 1Å are ideal for studying individual atoms

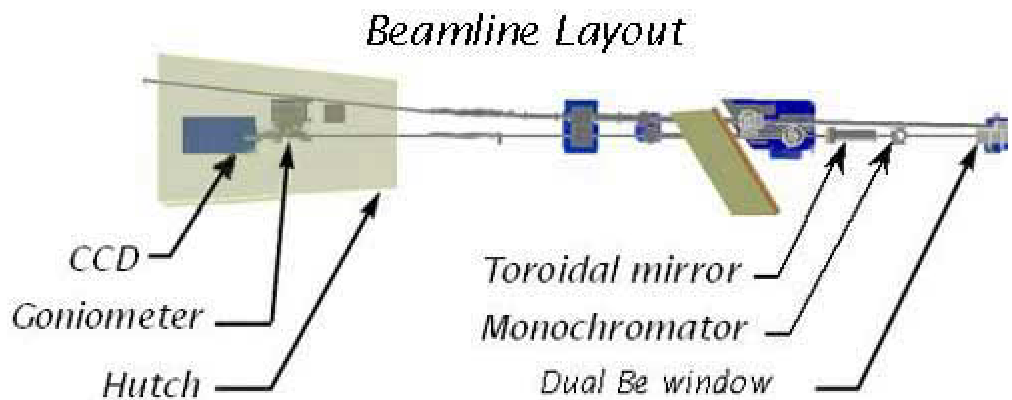




SR Beam Lines – cont.



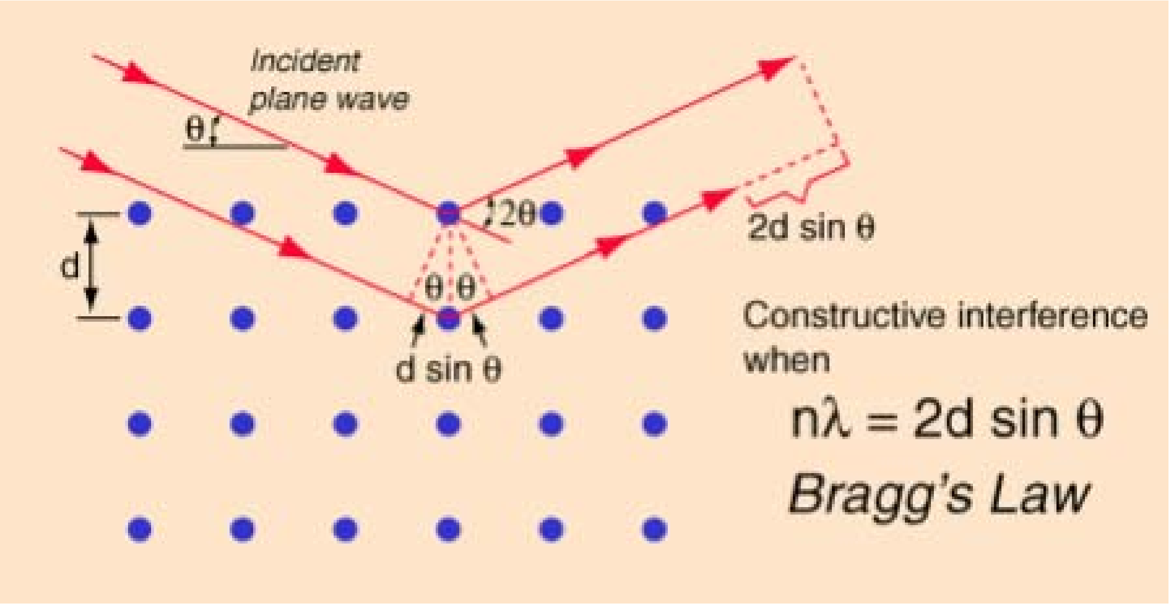




APS beam lines

BL 11.3.1 at ALS (dipole)

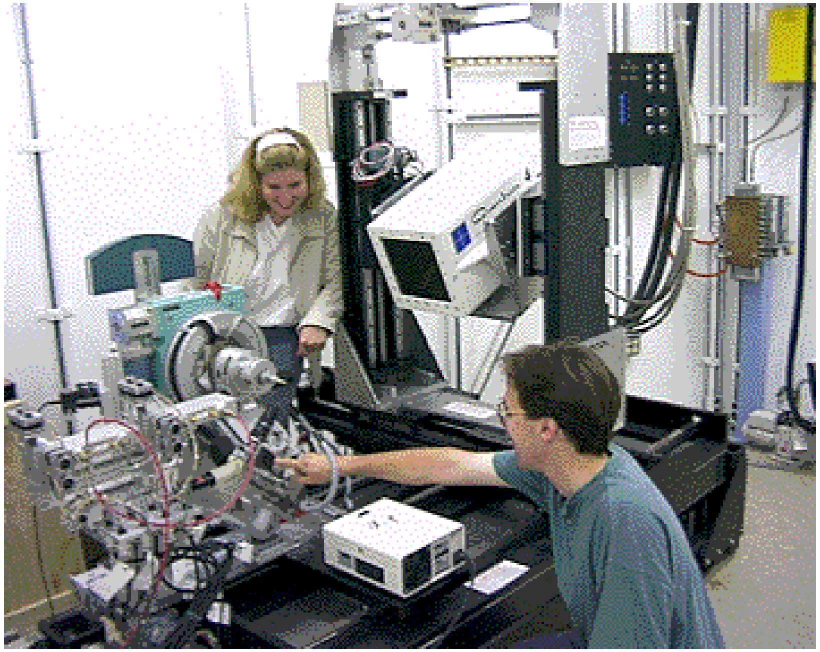
Monochromator – Bragg Reflection



SR Beam Lines – cont.

PX crystal mover
+ area detector

(SSRL BL 9-1)



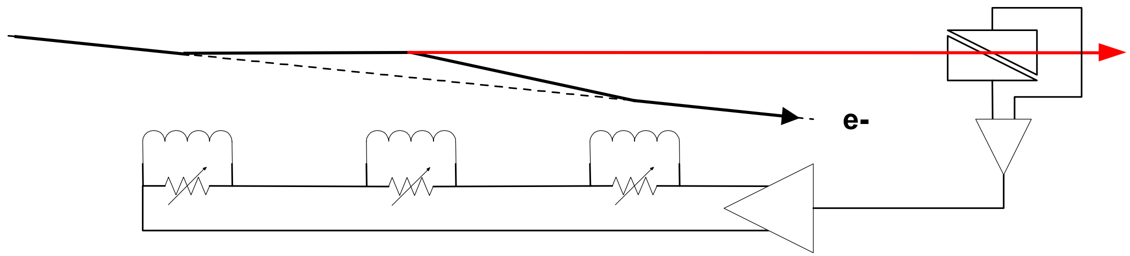
Ge or Si
fluorescence
detector

(APS)

Orbit Stabilizing Systems

~1980: "Local" vertical steering servos at SSRL (<1 Hz BW)

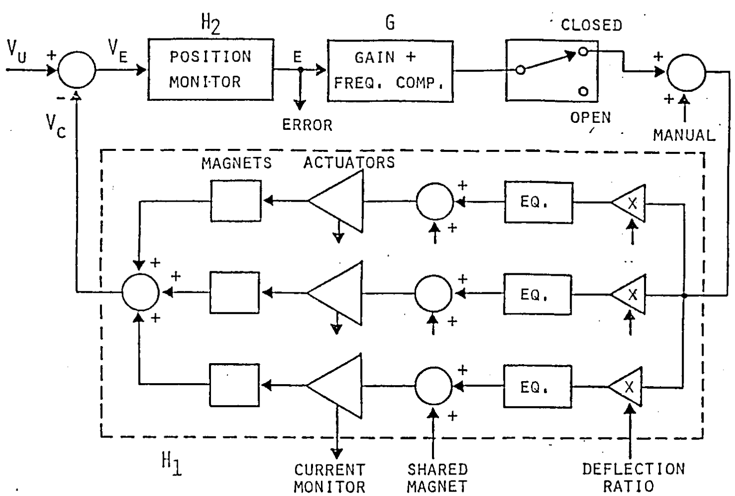
G. Brown, B. Salsburg, R. Hettel



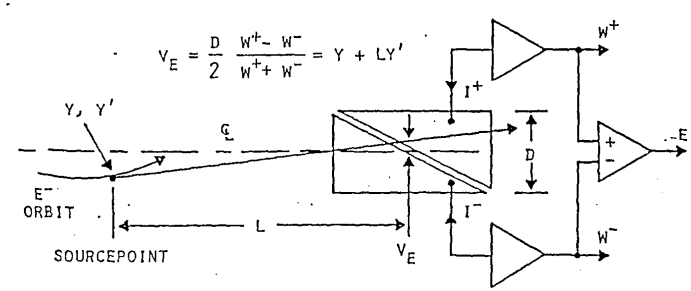
1982: Improved local steering servos at SSRL (~150 Hz BW)

R. Hettel

$$\frac{V_e}{V_u} = \frac{1}{1 + G H_1 H_2 (i\omega)}$$



3-MAGNET STEERING SERVO SYSTEM



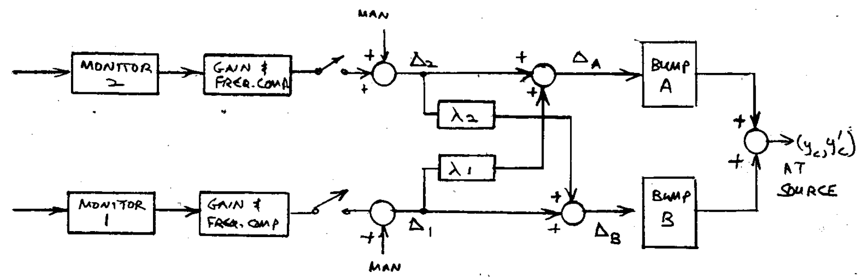
HELIUM ION CHAMBER POSITION MONITOR

Orbit Stabilizing Systems – cont.

1986: 4-magnet bump servos for SSRL beamlines at PEP (~100 Hz BW)

R. Hettel

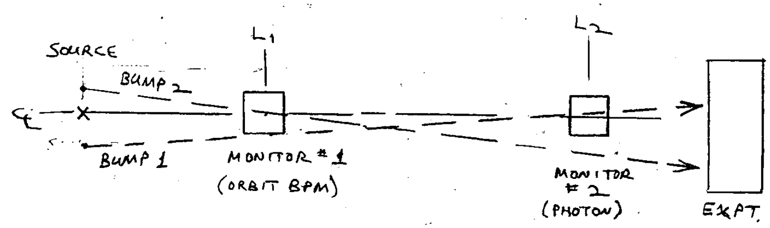
2-MONITOR, 4-MAGNET STEERING SERVO SYSTEM



BUMP A & BUMP B ARE LINEARLY INDEPENDENT, COMPENSATED

Δ_1 DRIVES BUMP 1 THAT CAUSES NO DISPLACEMENT AT MONITOR 2.

Δ_2 DRIVES BUMP 2 THAT CAUSES NO DISPLACEMENT AT MONITOR 1.



~1990: Improved 4-magnet servos at NSLS O. Singh, R. Nawrocky

Orbit Stabilizing Systems – cont.

NSLS Harmonic Feedback System 1988

L.H. Yu, R. Biscardi, J. Bittner, E. Bozoki, J. Galayda, S. Krinsky, R. Nawrocky, O. Singh, G. Vignola

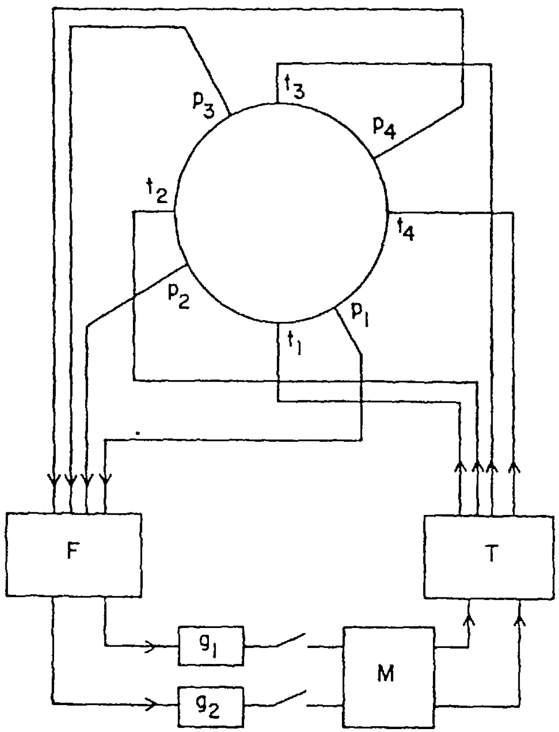
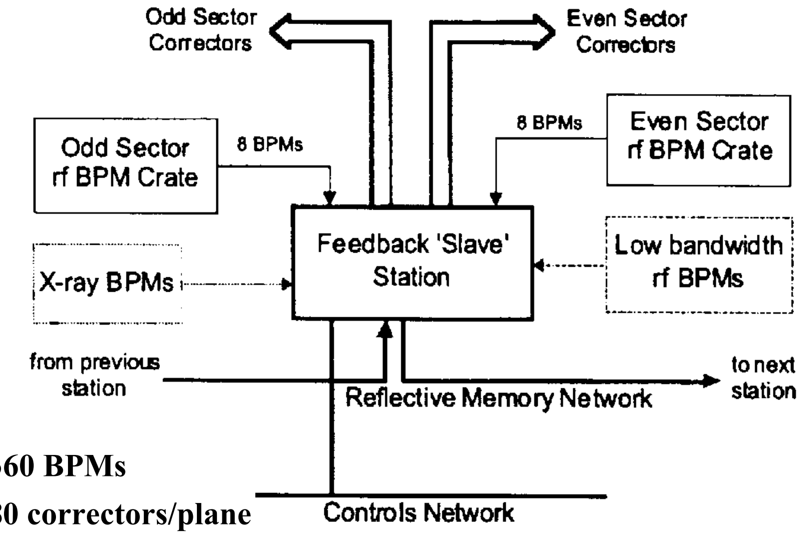


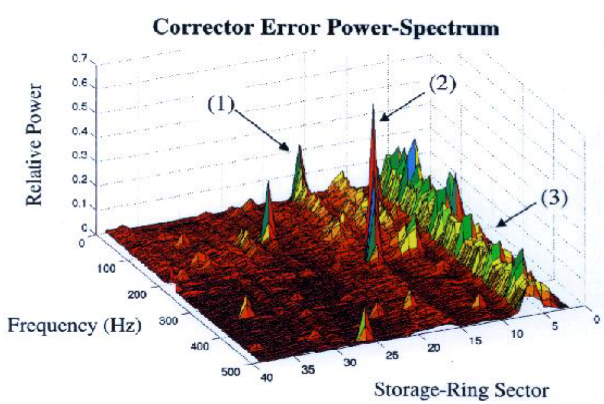
Fig. 1

APS SVD Global Feedback System - 1990s

J. Carwardine, Y. Chung, F. Lenkszus, et al.



- 360 BPMs
- 80 correctors/plane
- BPM de-spiking



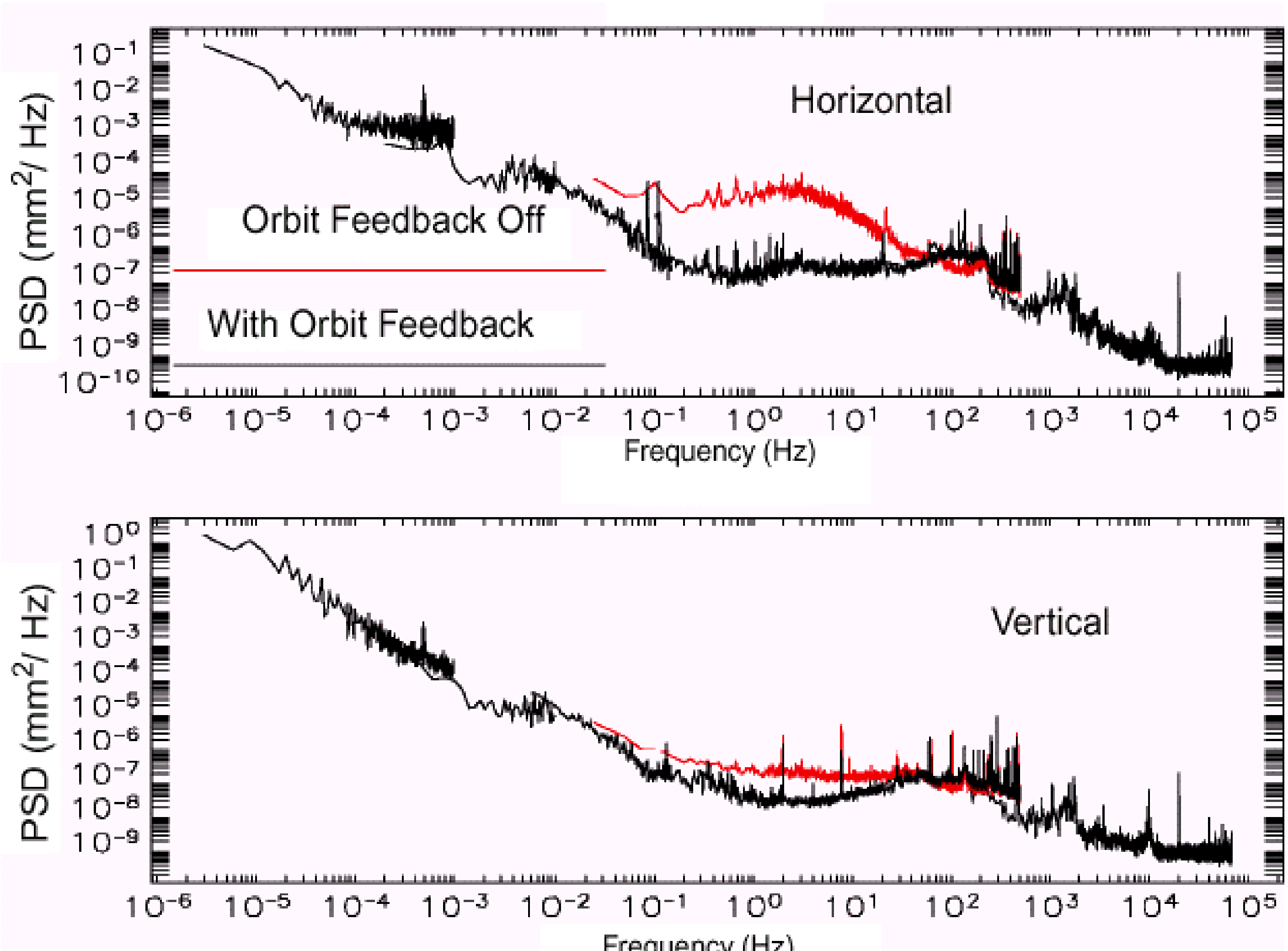
"DSP Scope"

1) Poor regulation of sextupole supply

2) Steering supply oscillating at 248 Hz

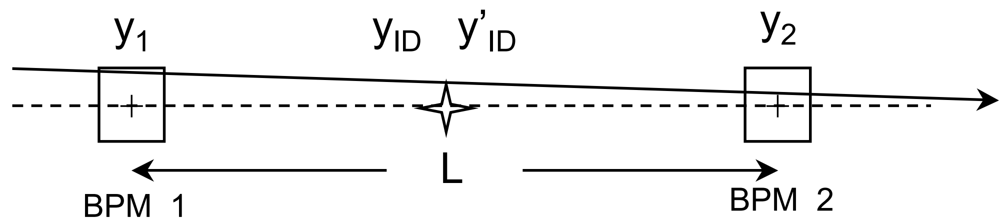
3) Bad BPM with broadband noise

Orbit Stabilizing Systems – performance at APS



Local vs. Global Feedback

Local correction:



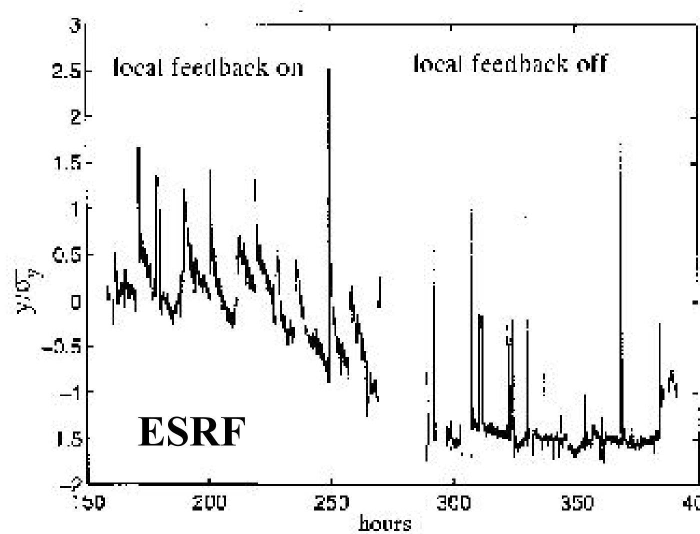
$y_{ID} = (y_1 + y_2)/2$ $\langle y^2_{ID} \rangle = \Delta y^2/2$ $y'_{ID} = (y_1 - y_2)/2L$ $\langle y'^2_{ID} \rangle = \Delta y^2/2L^2$

Δy = measurement error

e.g., $\Delta y = 10\ \mu$m, L = 3 m $\Rightarrow$ **7 μm rms** position error, **2.4 μrad rms** angle error

$\Rightarrow$ **want L to be large**

Multi-loop crosstalk $\Rightarrow$ reduced performance



Global correction:

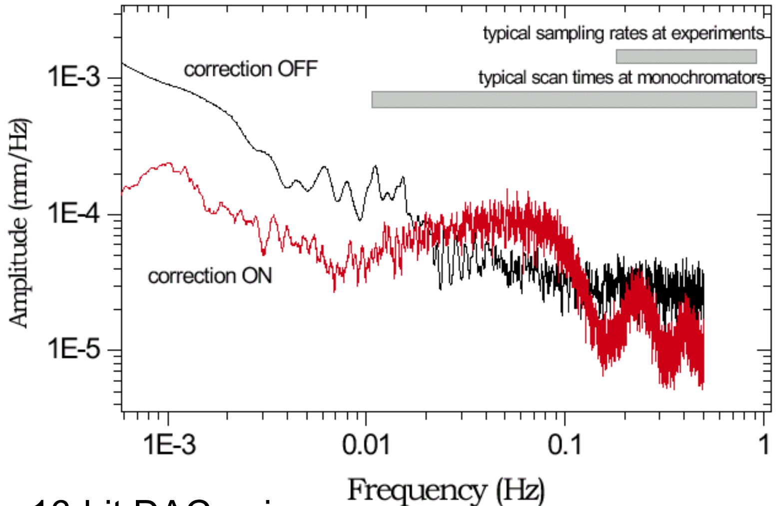
- reduced set of correction eigenvectors filters response to BPM noise

  lower spatial BW, more BPMs in average

- correction matched to most likely disturbances

Orbit Feedback - Corrector Resolution

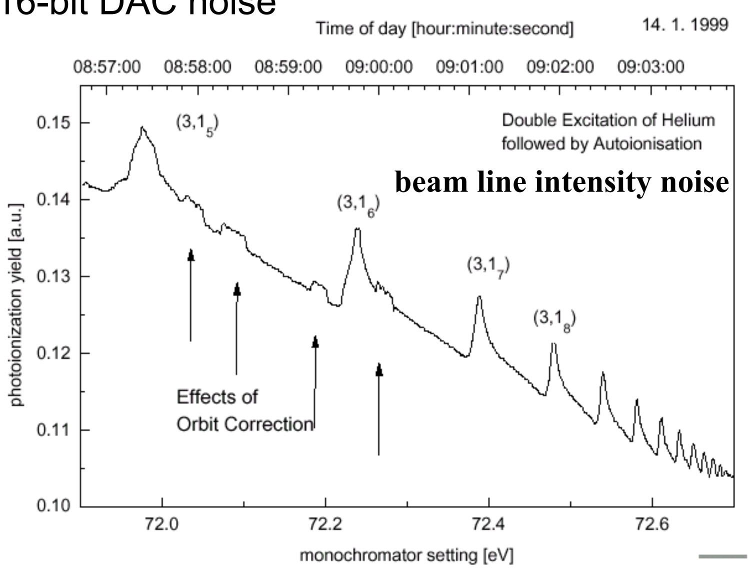
R. Mueller et al., BESSY II



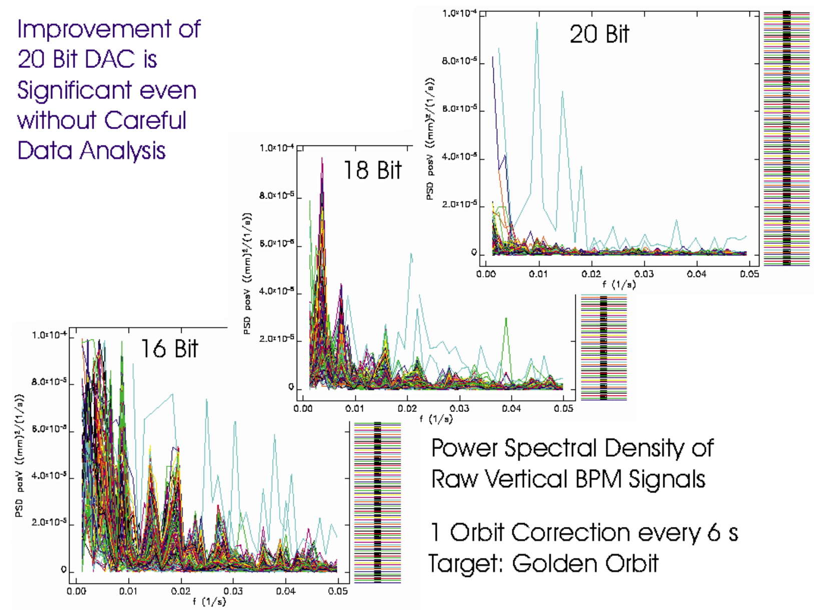
16-bit DAC noise

Noise from 16-bit DACs solved with 24-bit DACs (~20-bit ENOB)

(feedback cycle rate = 0.2 Hz)



Improvement of 20 Bit DAC is Significant even without Careful Data Analysis



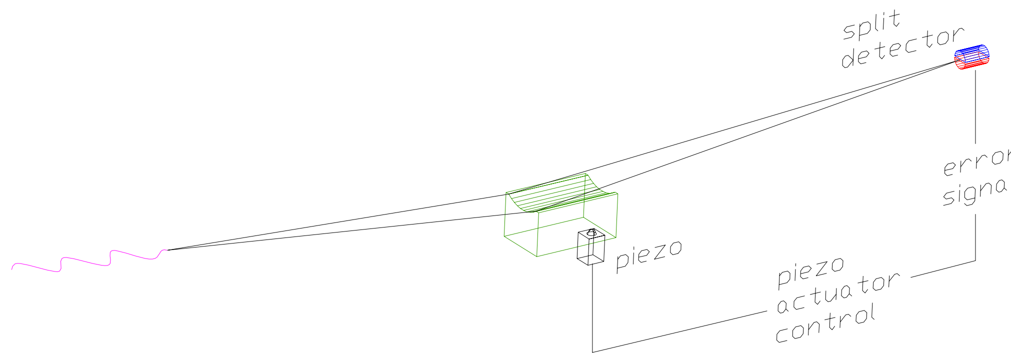
Power Spectral Density of Raw Vertical BPM Signals

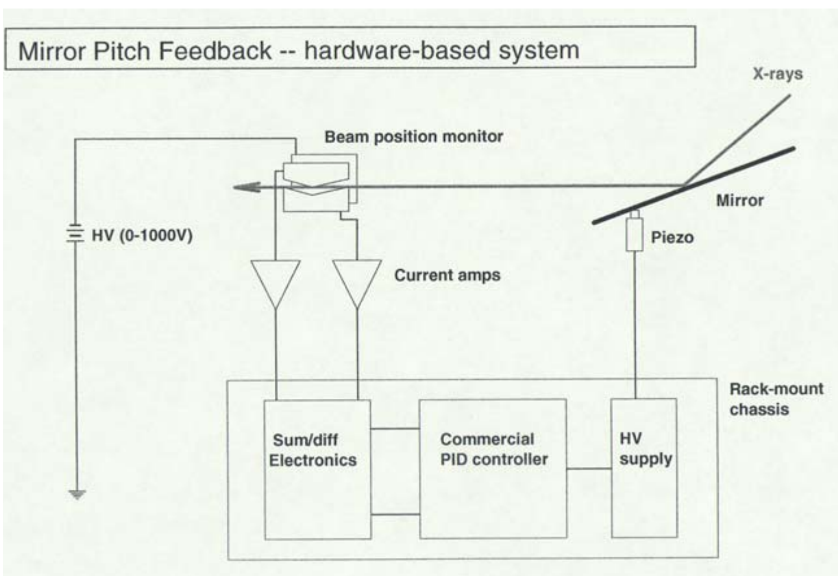
1 Orbit Correction every 6 s
Target: Golden Orbit

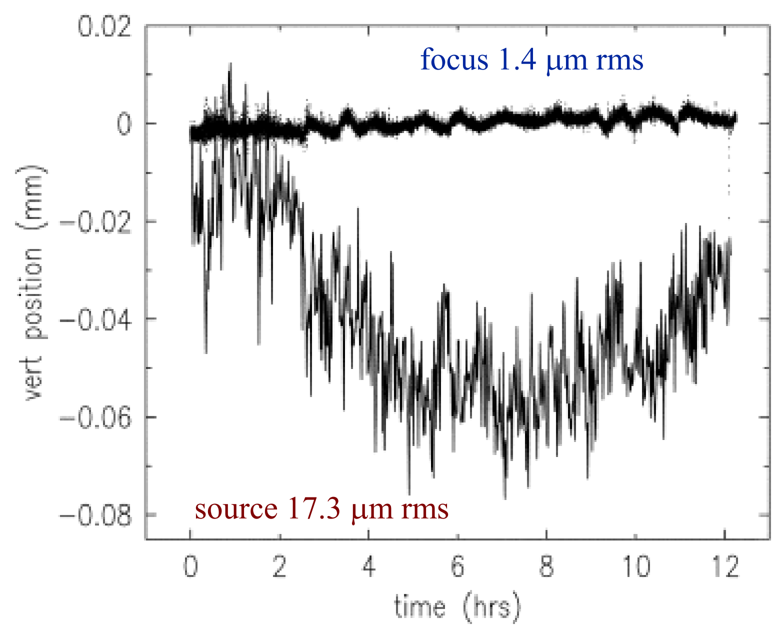
Mirror Feedback

T. Rabedeau, SSRL

- error signal obtained from position sensitive detector near beam focus
- error signal used to control piezo high voltage
- piezo provides mirror fine pitch control with typical full range of motion +/- 30 μrad or +/- 0.6mm or more focus motion



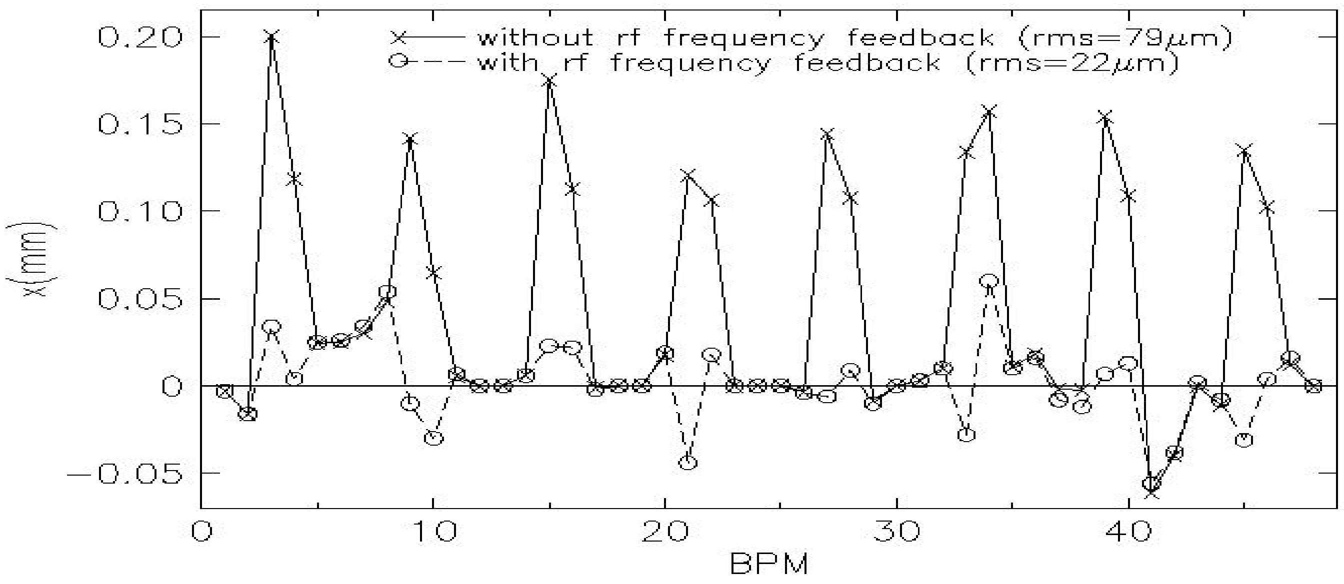




RF Feedback

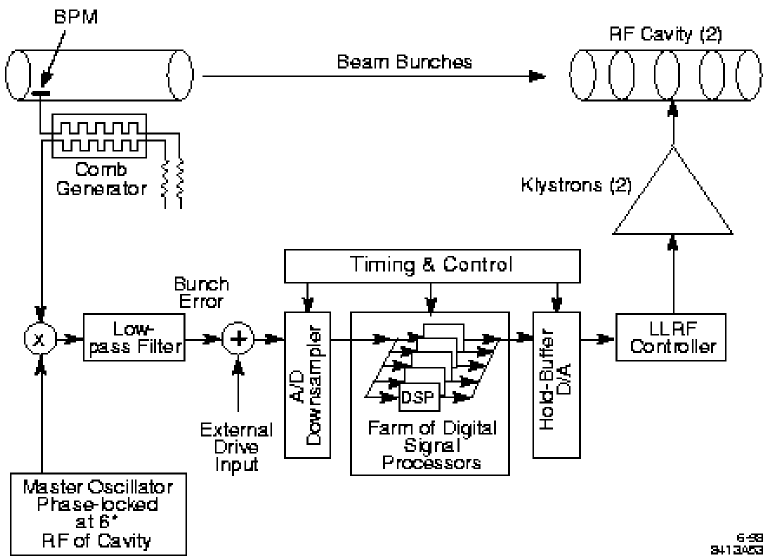
- Ring circumference change causes energy change
- Energy change causes dispersion orbit
- Correct dispersion orbit by changing rf frequency, not with orbit correctors

$$\Delta C/C = \alpha_c\, \Delta E/E = \Delta f_{RF}/f_{RF}$$



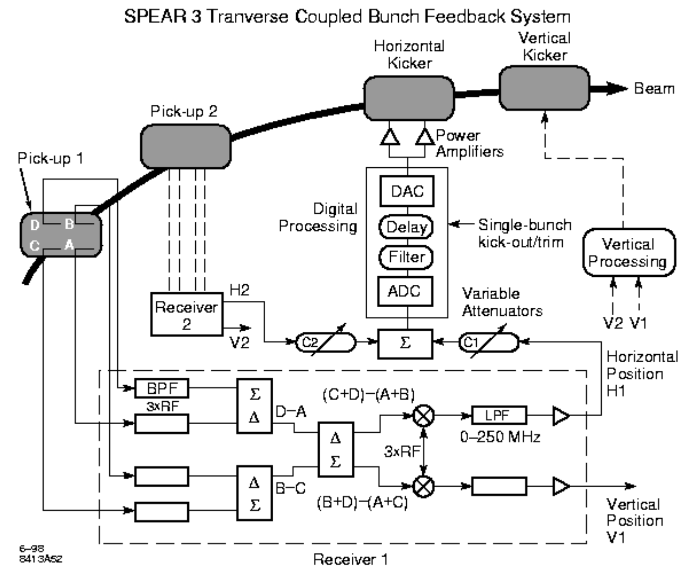
J. Safranek, NSLS

Multibunch Stabilization



Longitudinal Feedback

J. Fox et al., SLAC



Transverse Feedback

W. Barry et al., ALS

Harmonic Cavities

- increase bunch length and Touschek lifetime
- induce tune spread to damp multibunch instabilities **(Landau damping)**

ALS 1.5 GHz cavity

J. Byrd, R. Rimmer et al.

Importance of Brightness: 3rd Generation Sources

Spectroscopy experiments:

- Achieve the highest spectral resolution when the slits are narrowed.
- Photon beam should have small vertical size and angular divergence so that most of the flux from the source can pass through the narrowed entrance slits and strike the dispersing element at nearly the same angle.

Crystallography experiments:

- Match incident beam to small crystal size
- Maintain sufficient angular resolution to resolve closely spaced diffraction spots

$\Rightarrow$ - Minimize beam size and divergence

- Maximize flux within small phase space volume: **brightness**

Flux and Brightness: Definition of Terms

Spectral flux $F(\omega)$:

- Number of photons emitted per unit time in a small bandwidth $\Delta\omega/\omega$, usually taken to be 0.1%, centered at frequency ω (photons/s/0.1% BW).

(Note: $F(\omega)$ is actually spectral density)

Angular flux density $dF(\omega)/d\theta_{hor}$:

- Number of photons per unit time in bandwidth $\Delta\omega/\omega$ emitted into a horizontal angle $d\theta$, integrated in the vertical plane (photons/s/mrad/0.1% BW).
- Weak dependence on emittance; good metric for large samples.

Spectral flux density $dF(\omega)/d\theta_{hor}$/area:

- Number of photons per unit time in bandwidth $\Delta\omega/\omega$ emitted into a horizontal angle $d\theta$ per unit source area (photons/s/mm^2/mrad/0.1% BW).
- Good figure of merit for experiments requiring a small focused beam size but which can tolerate some angular beam divergence (e.g. measurements of protein crystals having a sufficient mosaic spread).

Flux and Brightness: Definition of Terms – cont.

Spectral brightness B(ω) :

- Spectral flux density in transverse source phase space: number of photons per unit time in a 0.1% bandwidth normalized to the phase space volume (photons/s/mm^2/mrad^2/0.1% BW).

$$B_0(\omega) = \frac{F(\omega)}{4\pi^2 \sigma_{phx} \sigma'_{phx} \sigma_{phy} \sigma'_{phy}}$$

- For bending magnet and wiggler beams, the horizontal divergence σ'_{phx} replaced by the horizontal angle $\Delta\theta$ accepted by the beam line or experiment.

- Important for experiments requiring both small beam size and low angular divergence (e.g. micro-focusing applications and crystallography on nearly perfect crystals) or that exploit transverse beam coherence (e.g. speckle).

Horizontal brightness:

- Brightness integrated in the vertical plane (photons/s/mm^2/mrad/0.1% BW)
- Good metric for experiments with sufficient vertical acceptance (e.g. macromolecular crystallography). Modest vertical emittance OK.

Another Metric...

Flux in sample acceptance phase space (photons/s/mm2/mrad2/0.1% BW)

- Quantity of interest for most experiments is the number of usable photons delivered to a sample.

- This quantity is dependent on the mapping of source phase space to sample acceptance phase space via the optical transport system.

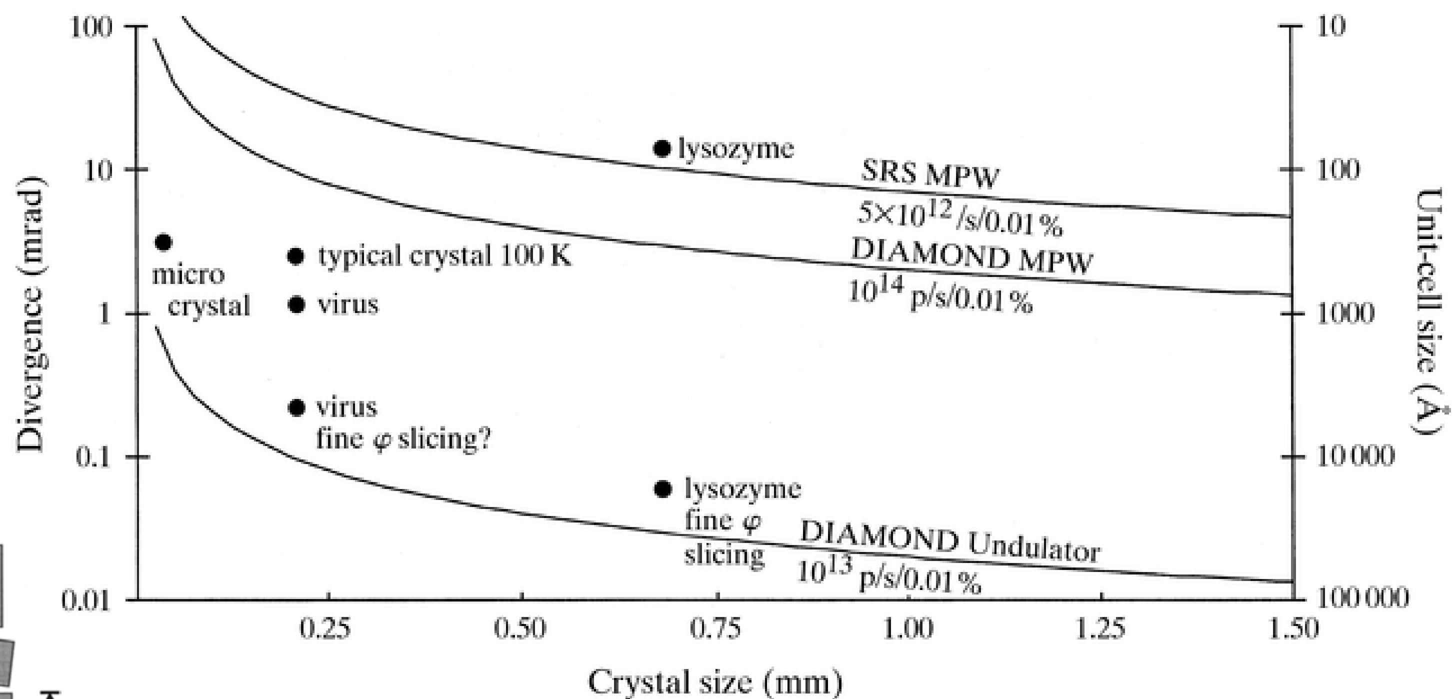
- Optimal performance is achieved when the optically transformed source phase space matches the sample acceptance phase space.

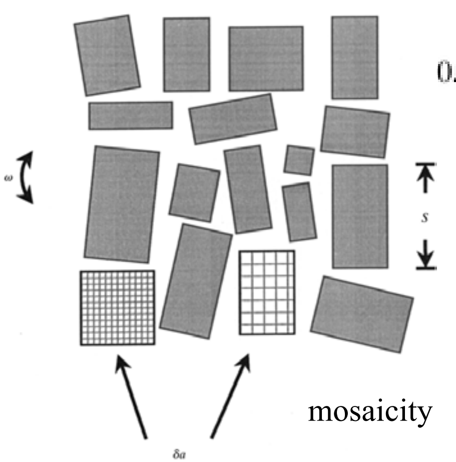
- For samples requiring modest collimation and spot size (e.g. macromolecular crystallography), moderate emittance machines can approach performance of low emittance machines:

e.g. The 0.5 $mm^2 mrad^2$ acceptance of a 0.1-0.3 mm square crystal having a mosaic spread of 3 mrad would be under-filled by the ~0.05 mm-mrad x 0.001 mm-mrad source phase space of an undulator in a very low emittance ring. A wiggler on a moderate emittance machine (i.e. 2^{nd} generation) can compete with modern machines in these cases.

Crystal Phase Space Acceptance

C. Nave





3^{rd} Generation Storage Ring SR Sources

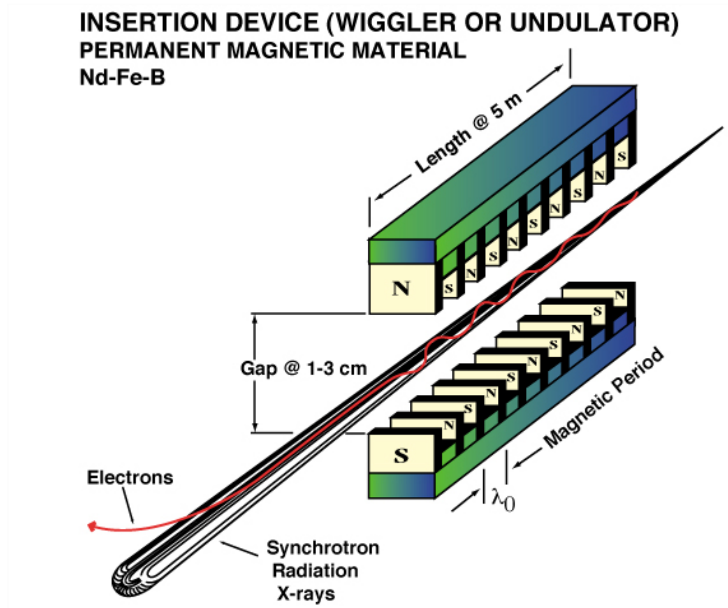
High brightness

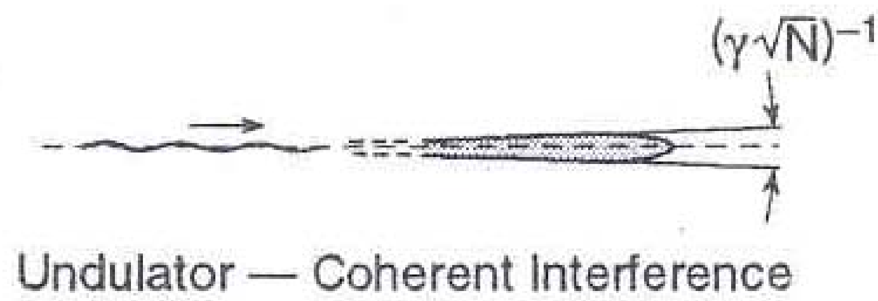
$\sim 10^{19}$ compared with $\sim 10^{16}$ for 2^{nd} generation

Low emittance

~1-20 nm-rad

Undulator sources





$\sigma_x \sim$ 0.1-0.5 mm $\quad \sigma_y \sim$0 .02-0.05 mm

$\sigma_x' \sim$ 0.02-0.1 mrad $\quad \sigma_y' \sim$ 0.01 mrad

(N = ~100)

Undulators – partial history

1947: Theory by Ginzburg, USSR

1953: Motz et al. build mm-visible undulator at Stanford

1970s: Undulators installed in storage rings at Lebedev Institute in Moscow, Tomsk Polytechnic Institute

1981: Halbach et al. build 1st permanent magnet undulator for SSRL

PMs allow shorter period devices than electromagnets

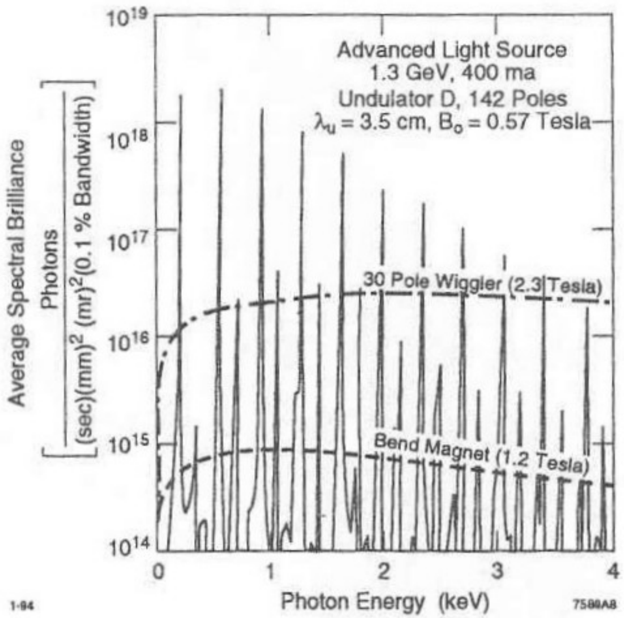
1987: Elliptical polarized undulator (EPU) at HASYLAB

1990: Mini-gap (6 mm) undulator at NSLS

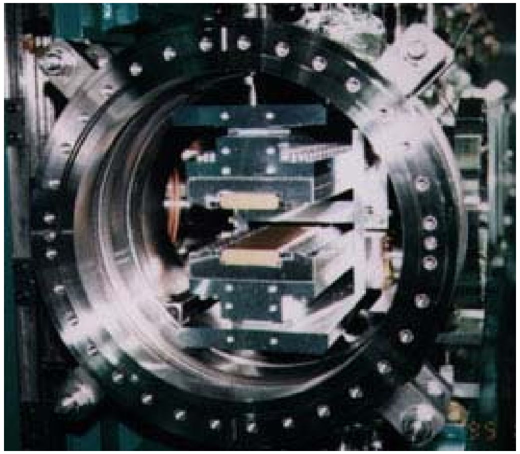
1991: In-vacuum undulator at Photon Factory

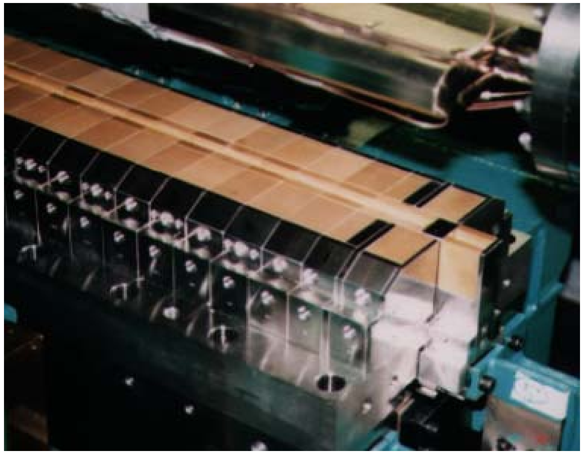
1993: Adjustable phase undulator (APU), SSRL

Klaus Halbach and Kwang-Je Kim, 1986



4.5 m in-vacuum undulators at SPring-8

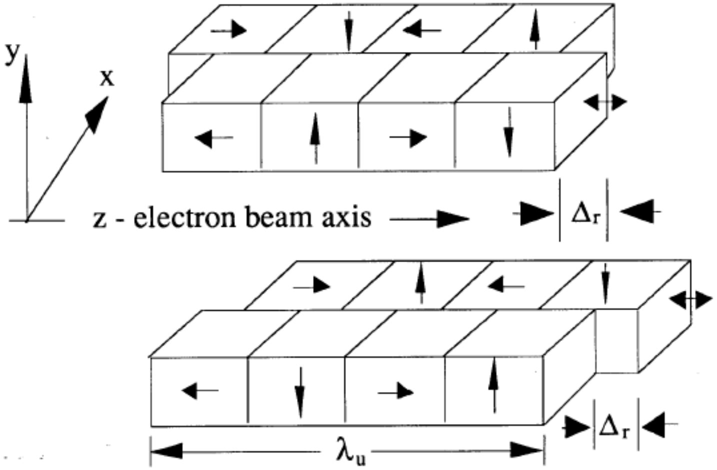




EPU with an APU

S. Lidia, R. Carr

based on PM EPU design by
S. Sasaki et al.



3^{rd} Generation Storage Ring SR Sources – partial list

1994: 1.5-GeV ALS (later 1.9 GeV)
1.5-GeV MAX II
2-GeV ELETTRA
6-GeV ESRF


ALS

1990s: 1.35-GeV LNLS, Brazil
1.5-GeV SRRC, Taiwan
1.9-GeV BESSY II
2-GeV PLS, Korea
7-GeV APS
8-GeV SPring-8, Japan

2001: 2.4-GeV SLS, Switzerland

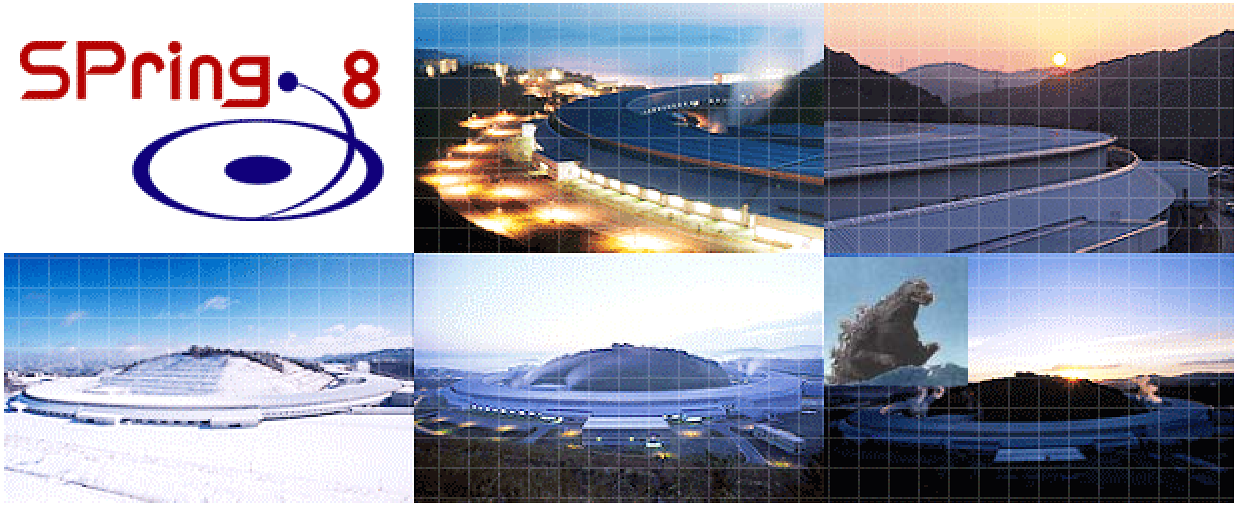
In progress:

700-MeV MAX III
2-GeV INDUS 2
2.5-GeV LLS, Barcelona
2.5-GeV SESAME, Jordan
2.8-GeV Soleil, France
2.9-GeV CLS, Saskatoon
3-GeV SPEAR 3
3-GeV DIAMOND, UK
3-GeV Australian Light Source
3.2-GeV CANDLE, Armenia
3-GeV MAX IV (?)
6-GeV PETRA-III, DESY
6.5-GeV AR, KEK

Old 3rd Generation Facilities – 6-8 GeV

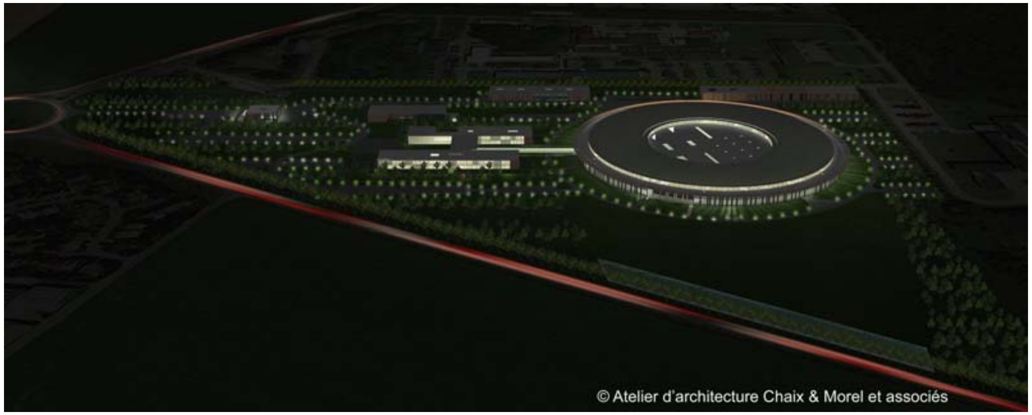
ESRF

APS

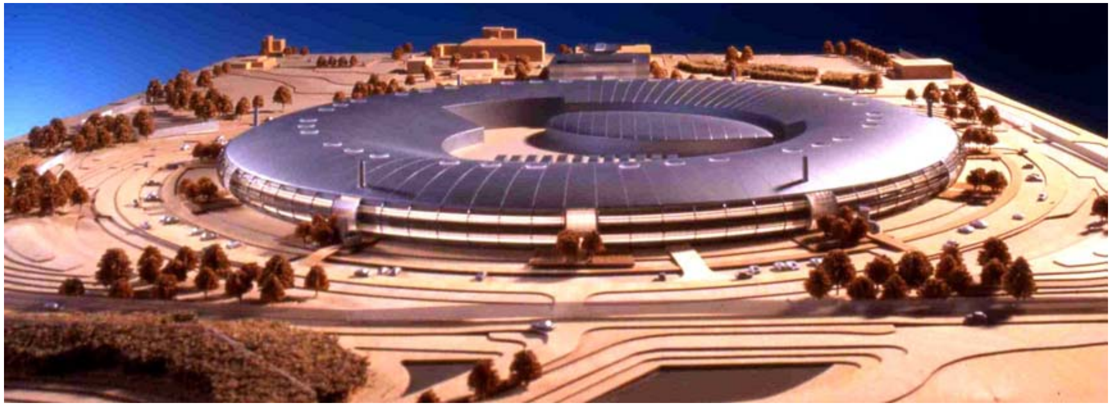


New 3rd Generation Facilities - ~3 GeV

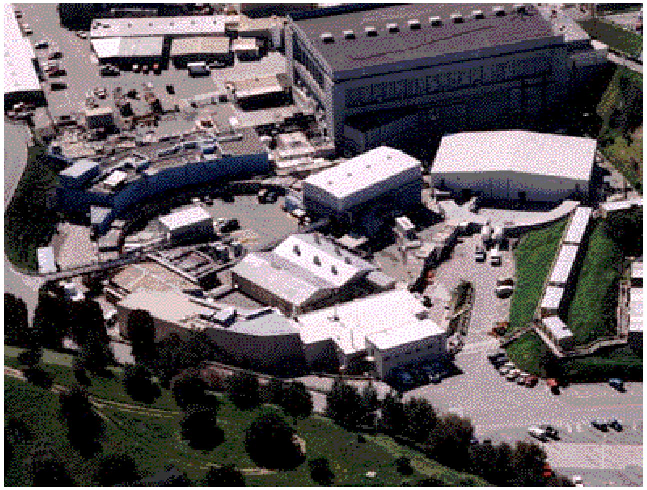
Canadian Light Source



Soleil (sans soleil, France)



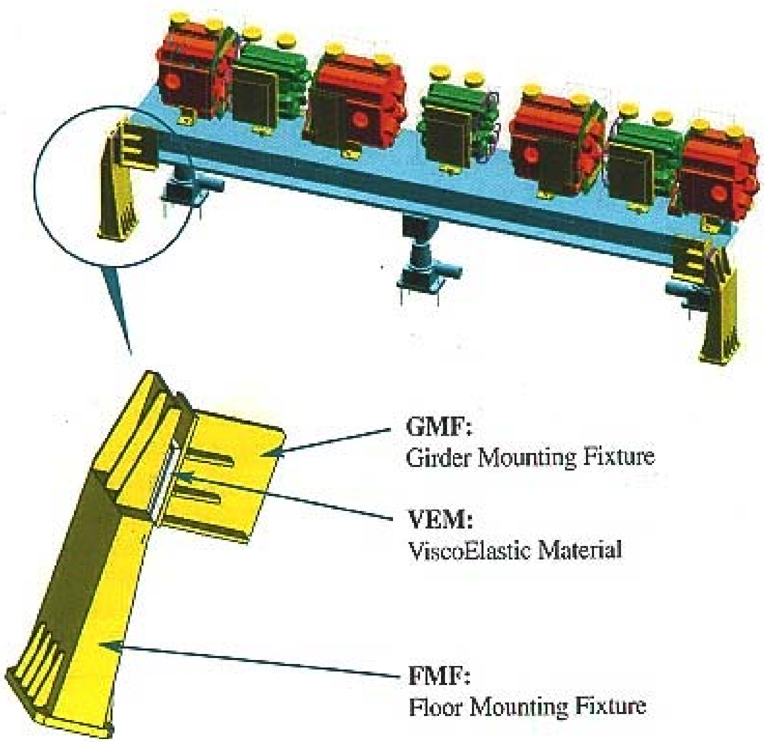
Diamond (UK)

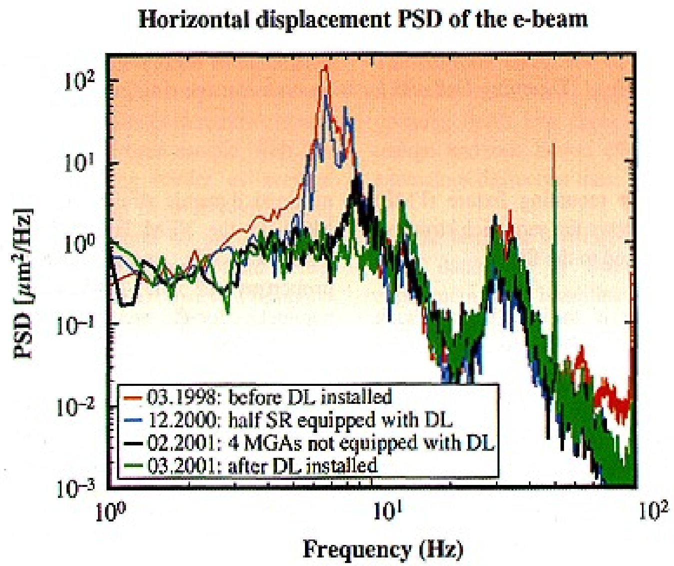


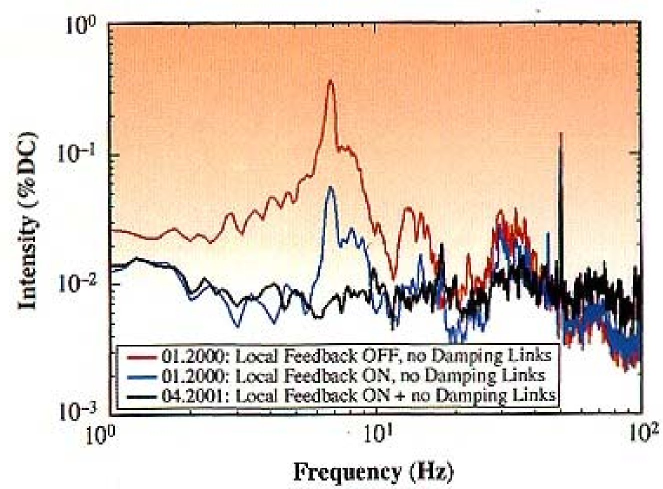
SSRL (SPEAR 3)

3rd Generation Facilities – Mechanical Stability

- Visco-elastic material used to damp girder vibration at APS
- ESRF added damping fixtures for girders





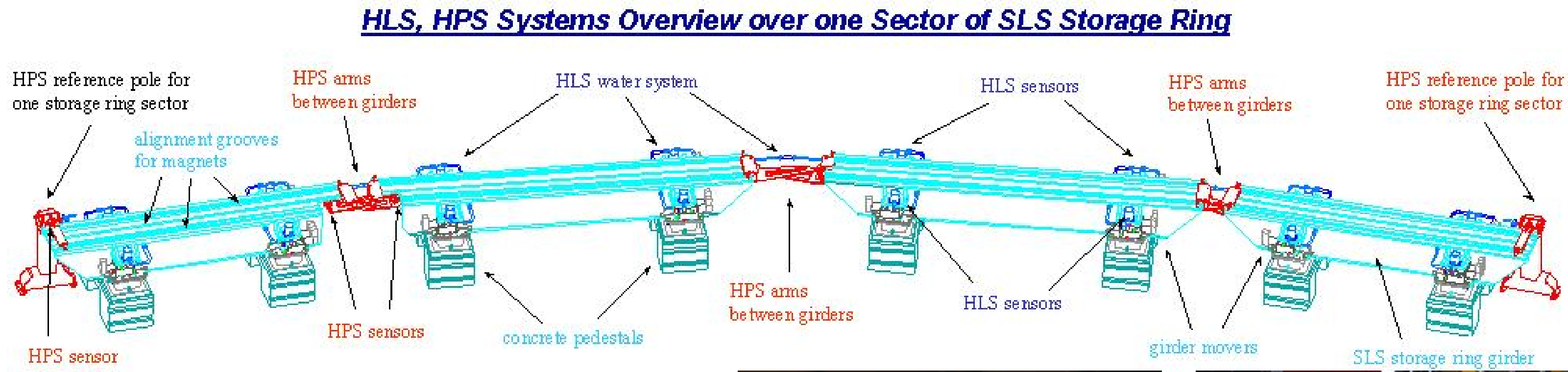


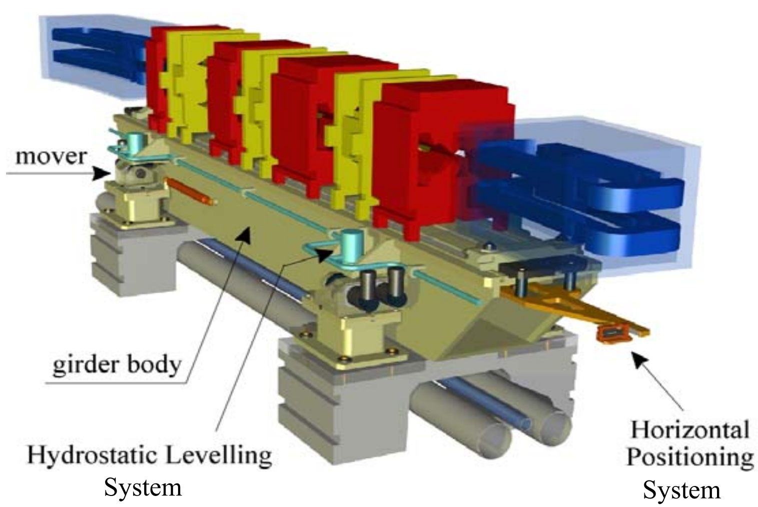
beam line intensity noise

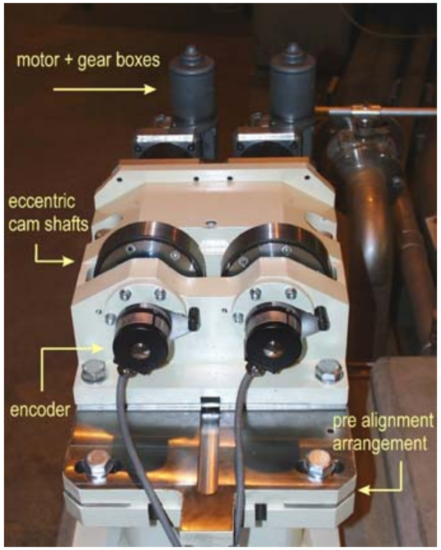
3rd Generation Facilities – Mechanical Stability

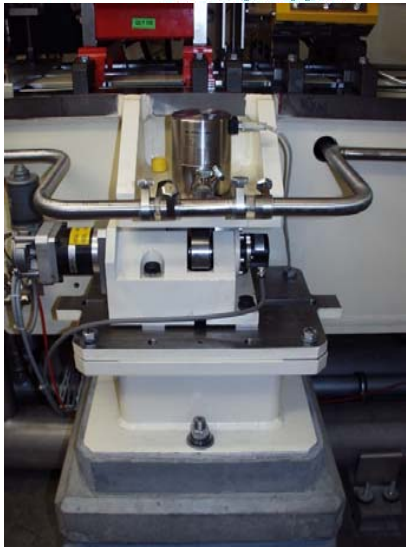
SLS Girder Mover System

V. Schlott and S. Zelenika et al. (conceived by G. Bowden, SLAC)



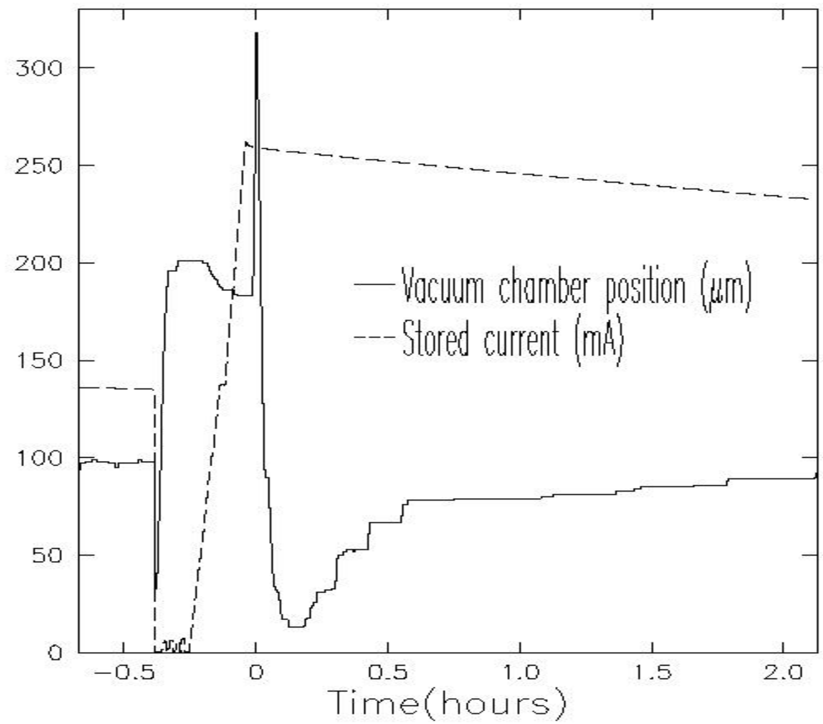






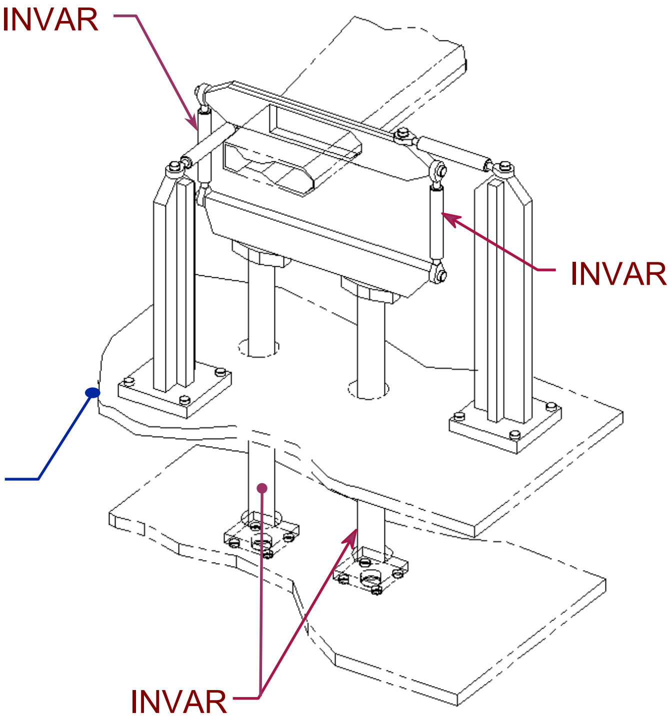
cam mover and hydrostatic level detector
(micron resolution)

3rd Generation Facilities – Mechanical Stability



NSLS chamber motion

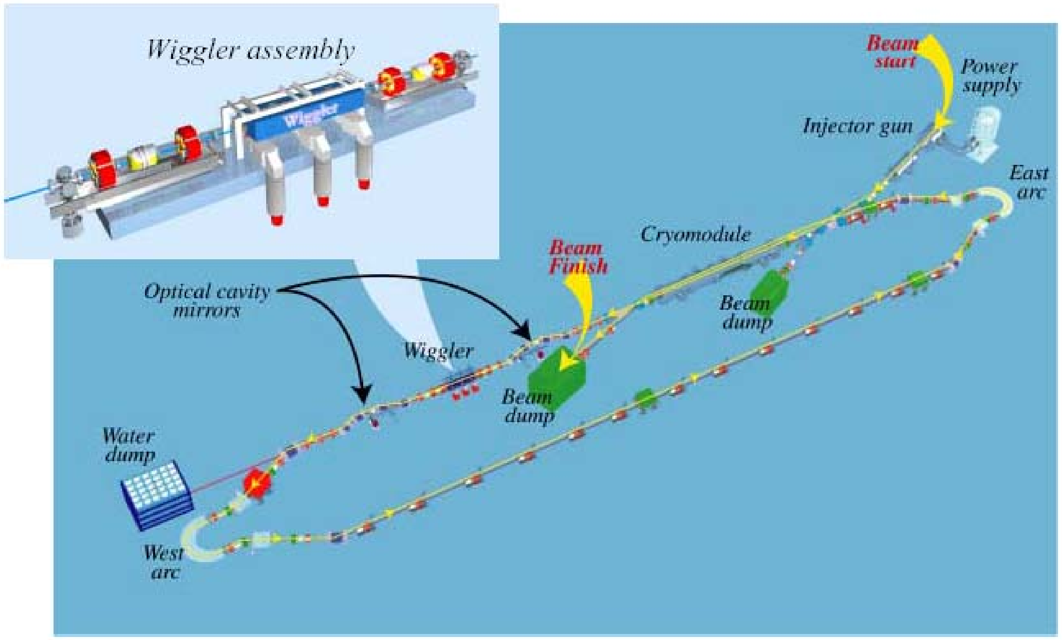
J. Safranek



SPEAR 3 chamber/BPM supports

3 μm/°C vert, 15 μm/°C hor

Other SR Sources



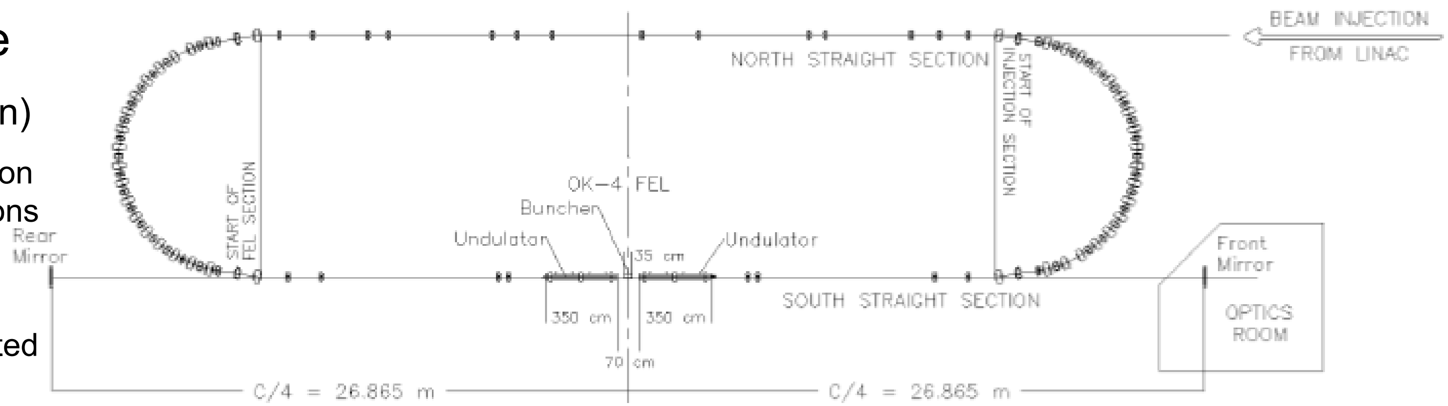
IR FEL at Jefferson Lab

UV FEL at Duke

(OK-4 optical klystron)

MeV photons by Compton backscatter of UV photons off 2nd e- bunch

Feedback needed to stabilize mirrors separated by 53 m



Improving 3rd Generation Sources

Extended spectral range for low energy machines

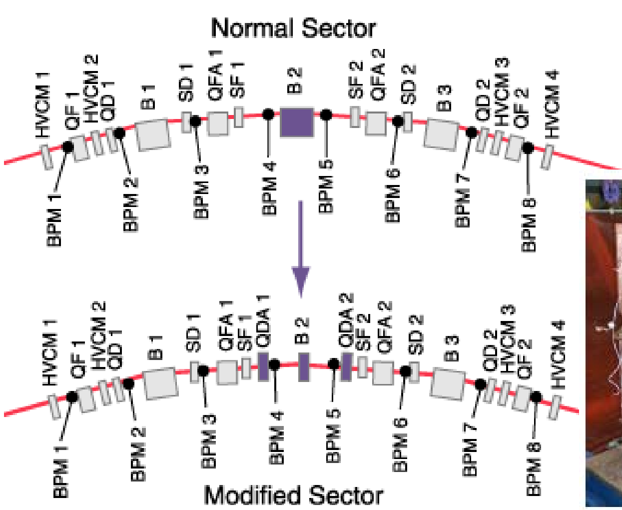
- Protein crystallography has become major application: high flux, 6 -12 keV

  Add superconducting “wavelength shifters” or wigglers

  B = ~5 T, E = 1.5 GeV

$$E_{crit}(\text{keV}) = \frac{3\hbar c\gamma^3}{2\rho} = 0.665\, B(T)\, E^2(\text{GeV}) = 7.5\ \text{keV}$$

compared with E_{crit} = 1.9 keV for 1.3 T dipole



ALS 5-T superbends

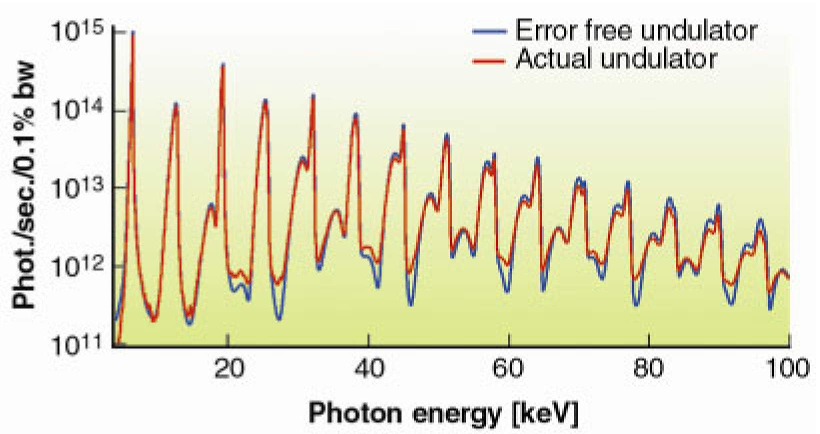
MAX-II superconducting wiggler (3.5 T)

Improving 3rd Generation Sources – cont.

Extended spectral range – cont.

- Use higher undulator harmonics

  requires high magnetic field quality: **shim poles**



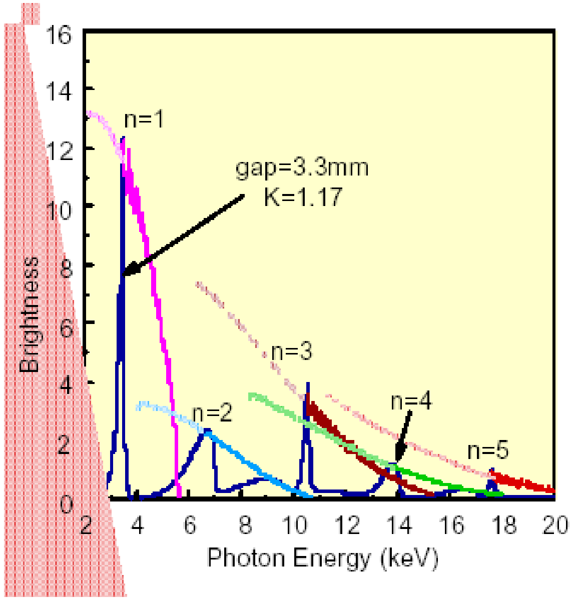
from ESRF

- Reduce undulator period and gap to reach higher fundamental:

  in-vacuum undulators

  e.g. NSLS Mini-Gap Undulator

  gap = 3.3 mm
  period = 12.5 mm
  B_{pk} = 1.0 T



G. Rakowsky et al.

Improving 3rd Generation Sources – cont.

Extended spectral range – cont.

- IR sources continue to be valuable, with THz sources gaining interest for research in collective excitations in solids, molecular dynamics, superconductor bandgaps, electronic and magnetic scattering, ultra-fast processes

    - storage ring FELs and optical klystrons

    - edge radiation (from dipoles)

Improving 3rd Generation Sources – cont.

Improve lattice brightness

- Reduce emittance by "leaking dispersion" from achromat

  ~ factor of 2 reduction

- Reduce horizontal-vertical emittance coupling from ~1% to ~0.1%

  $\sigma, \sigma' \sim \varepsilon^{1/2} \Rightarrow$ reduce vertical beam dimensions by ~3

Improving 3rd Generation Sources – cont.

Improve lifetime

- Increase Touschek lifetime:
  - Large-angle Coulomb scattering of particles in bunch results in longitudinal oscillations that can exceed momentum acceptance or dynamic aperture of ring $\Rightarrow$ **low lifetime**

$$\tau_{Touschek} \propto \frac{\sigma_{x'}\sigma_x\sigma_y\sigma_s\gamma^3\left(\delta p/p\right)^2}{N}, \quad N = \text{particles/bunch}$$

$\tau_{Touschek}$ = ~ 2-4 h for 1.5-GeV, 10s h for 3 GeV-8 GeV (dynap, gap limited)

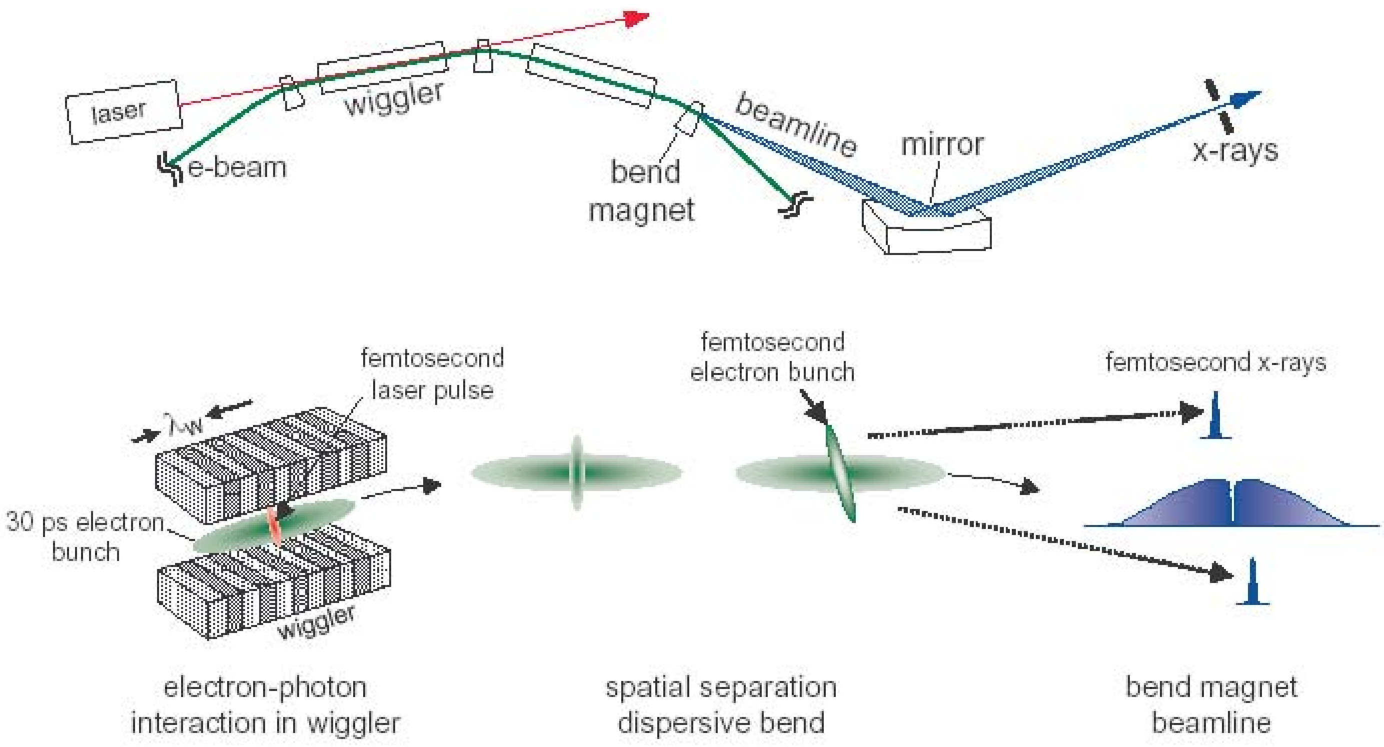
  - Can improve Touschek lifetime for given number of bunches and current by increasing bunch volume:
    - increasing bunch length with cavity (ALS, NSLS, ALADDIN, etc)
    - increase vertical beam size if experiment beam sized dominated by photon opening angle and/or focusing optics

- Increase dynamic aperture:
  - optimize tune working point
  - optimize lattice via beam-based calibration (LOCO)
  - correct orbit to be in center of magnets

Improving 3rd Generation Sources – cont.

Short bunch length

Femtosecond photons at the ALS



Zholents and Zolotorev, *Phys. Rev. Lett.*, **76**, 916,1996.

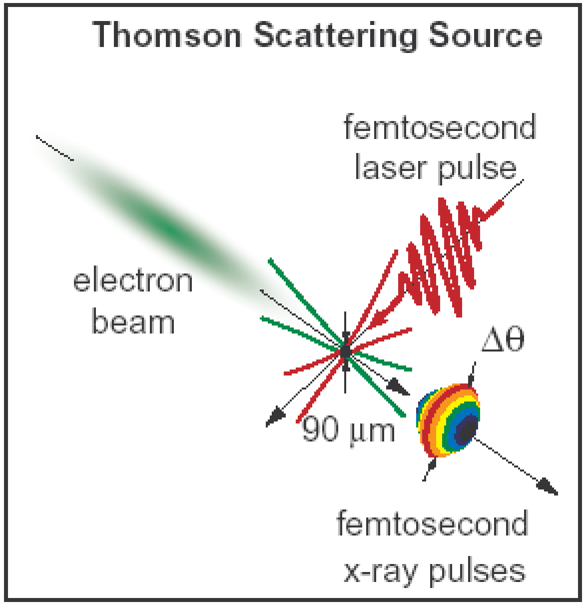
Thomson/Compton Scattering

- Electrons accelerated by low energy photon "electromagnetic undulator" field:

$$\omega_x = \frac{2\gamma^2(1-\cos\phi)}{1+K^2/2+\gamma^2\theta^2}$$

(electron energy assumed unchanged; otherwise, Compton scattering)

ϕ = incident angle of photons wrt electrons
ω_0 = incident photon freq = $2\pi c/\lambda_0$
ω_x = boosted photon freq
K = normalized vector potential of laser field
$\approx 8.5 \times 10^{-9} \times I^{1/2} \times \lambda_0$ [μm]
I = peak laser intensity [W/cm^2]
θ = view angle



- Bunch length: transit time of laser pulse across electron beam:

~200 fs @ 90° for 50 μm electron spot size
~10 ps @ 180° for 10 ps electron bunch length

- At LBNL (Weemans et al.):

$\phi = 90^o$ λ_0 (laser) = 0.8 μm
E_{e-} = 50 MeV
$\sigma_{x,y}$ (e-) = 50 μm
σ_s (e-) = 10 ps

(Terawatt Ti-Al_2O_3 laser $\Rightarrow$ K = ~1
σ_r (laser) = ~50 μm
σ_s (laser) = ~100 fs
laser energy/pulse = 125 mJ

Leemans et al., *Phys. Rev. Lett.*, 1996.
Schoenlein et al., *Science*, 1996.

$\Rightarrow$ **λ_x = 0.4 Å (~30 keV)**

Improving 3rd Generation Sources – cont.

Improve stability

- Top-off injection
  - stabilizes thermal load on accelerator and beam line components
  - reduces or eliminates impact of short lifetime from Touschek, small gap insertion devices, etc.

- Facility temperature control (air conditioning)
- A host of passive and active stabilizing measures

THE MAIN TOPIC OF THIS CLASS!

4^{th} Generation Light Sources

Users want more!

- higher brightness

  small, intense beams

  angstrom and sub-angstrom radiation

  diffraction limit ($\varepsilon = \lambda/4\pi$)

- higher coherence

  time-resolved holography, phase retrieval

  single-shot holography

- shorter bunches

  femtosecond phenomena in materials

  pump-probe with femtosecond timing resolution

Transversely coherent spectral flux:

$$F_{coh}(\lambda) = (\lambda/2)^2 B_0(\lambda)$$

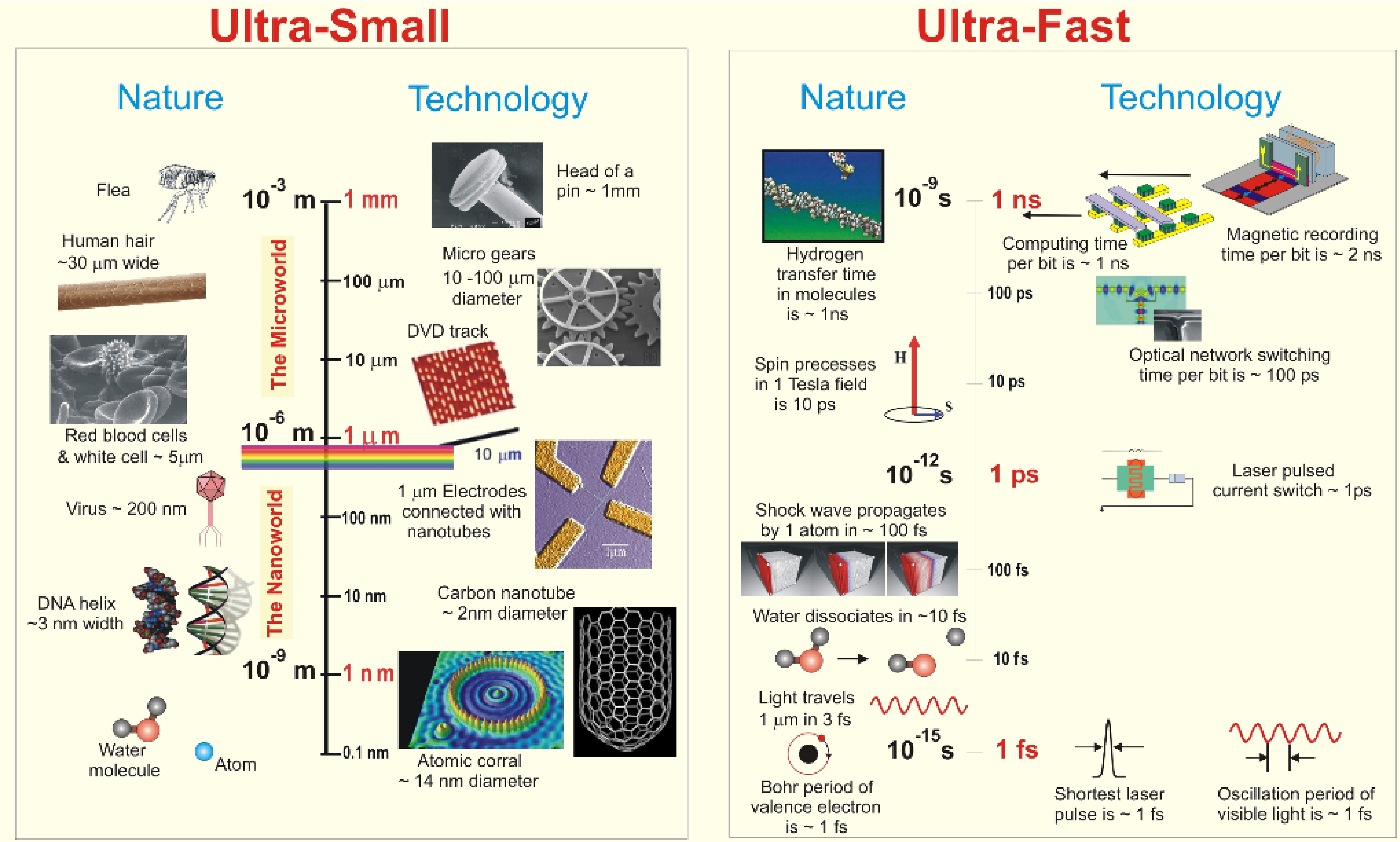
$$B_0(\lambda) = \frac{F(\lambda)}{4\pi^2 \varepsilon_x \varepsilon_y}$$

If $\varepsilon = \lambda/4\pi$ in both planes,

$$F_{coh}(\lambda) = F(\lambda)$$

i.e. all photons are coherent

Why 4th Generation Light Sources?



J. Galayda, LCLS presentation to 20-Year BES Facilities subcommittee, Feb. 2003

4th Generation Light Sources – cont.

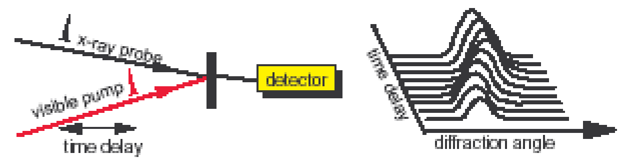
Structural Dynamics in Condensed Matter

fundamental time scale for atomic motion
vibrational period: $1/\nu_{vib} \sim 100$ fs

- ultrafast chemical reactions
- ultrafast phase transitions
- surface dynamics
- ultrafast biological processes

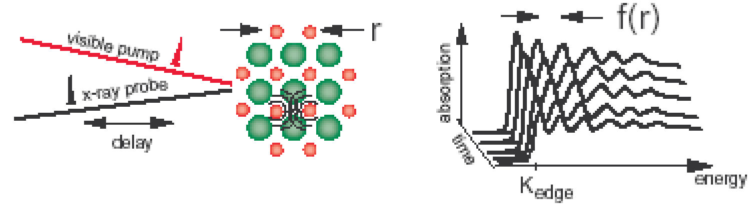
Rapidly emerging filed of research
Physics, Chemistry and Biology

time-resolved x-ray diffraction



ordered crystals - phase transitions, coherent phonons

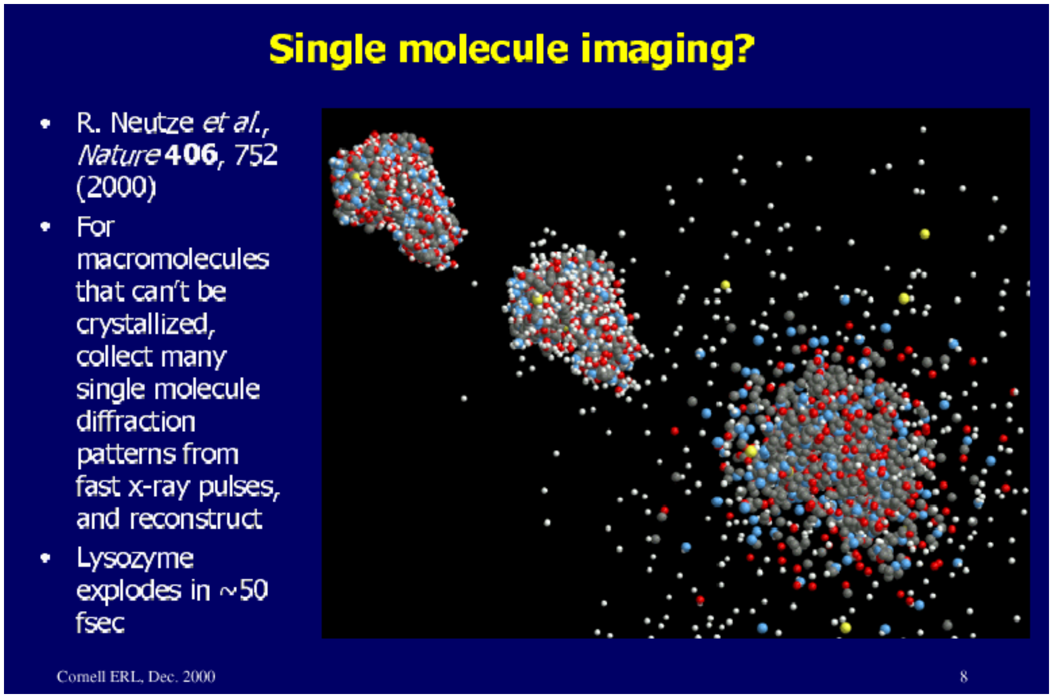
time-resolved EXAFS, NEXAFS, surface EXAFS

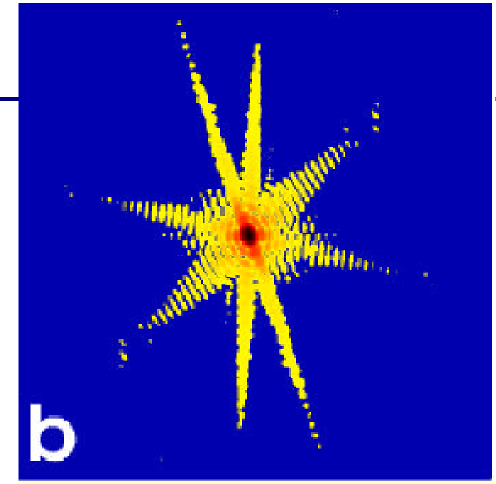


complex/disordered materials - chemical reactions
surface dynamics
bonding geometry

From R. Schoenlein, LBNL

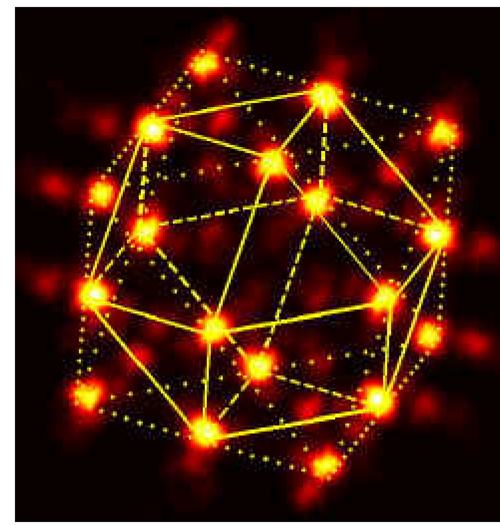
4th Generation Light Sources – cont.





Coherent X-ray scattering

⇒ reconstruction to 3D shape



Phys. Rev. Lett. 82 , 4847

Points of light. This x-ray hologram shows the positions of cobalt atoms to within 0.1 Å .

4th Generation Light Sources – Options (so far)

Ultra-low emittance storage rings

- Diffraction limited emittance
- High average brightness
- High transverse coherence
- Stable "CW" operation

Linac-based FELs

- Diffraction limited emittance
- High average brightness
- High peak current
- Huge peak brightness
- Full transverse, longitudinal coherence
- Femtosecond bunch lengths
- ~100 Hz repetition rate

Energy recovery linacs (ERLs)

- Diffraction limited emittance
- High average brightness
- Full transverse, longitudinal coherence

  from individual bunches
- ~10 kHz repetition rate
- Femtosecond bunch lengths
- Low peak current

  limits usefulness of short bunch

4th Generation Light Sources – Options

G. Shenoy, J. Arthur
X-Ray Science Workshop for ERL
Dec. 2000

	3rd Gen. (ESRF/APS/Spring-8)	ERL	XFEL Spontaneous	XFEL SASE
Bunch width	20-50 ps	< 3ps	< 200 fs	< 200 fs
Separation between Bunches	2µs-3 ns	> 800 ps	100ns - 10 ms	100ns - 10ms
Corresponding Bunch ~~Current~~ charge	~ 15nC	> 0.08nC	1nC	1nC
Corresponding Photon flux per bunch	10^8	> 10^7	10^9	10^{12}
Ave. Maximum Brilliance	~ 10^{21}	10^{22}	10^{18} - 10^{23}	10^{22} - 10^{27}
Peak Brilliance	~ 10^{24}	10^{25}	10^{29}	10^{33}
Beam ($\varepsilon_x/\varepsilon_y$)	~ Flat (100)	~ Round (1)	~ Round ~(1)	Round (1)

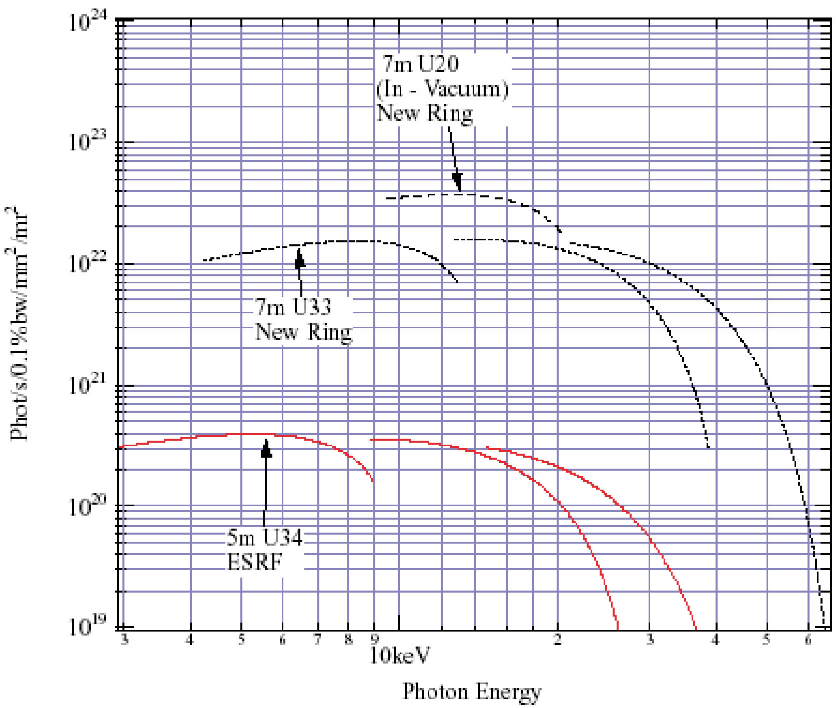
Wavelength ~10 keV, trans. coh. length, flux

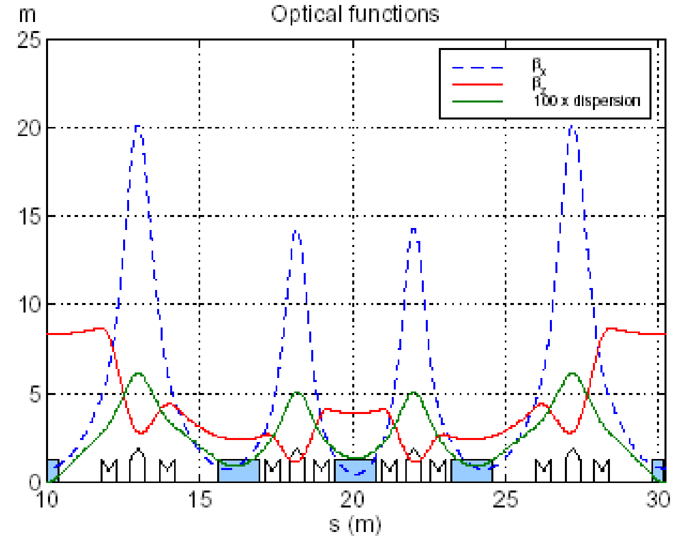
JA, GS

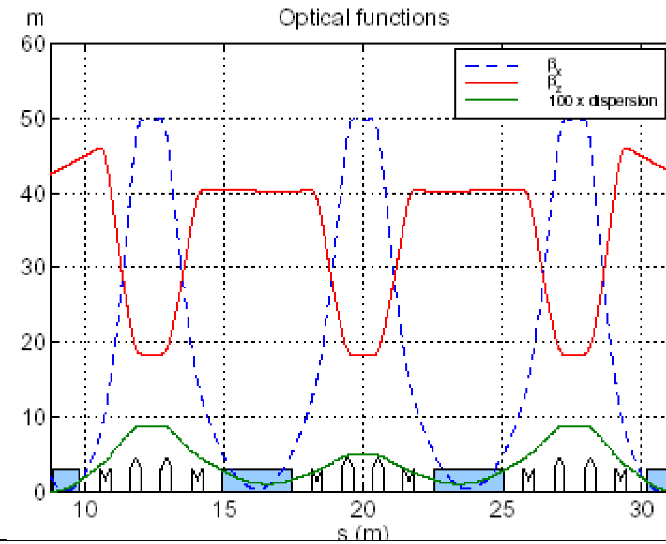
Ultimate Storage Ring Light Source

(A. Ropert et al., ESRF)

- E = 7 GeV
- C = 2 km
- ε_x = ~0.3 nm-rad
- 4 dipoles/achromat
- damping IDs

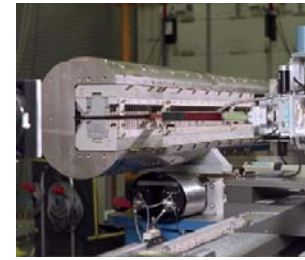






X-Ray Linac FELs

LCLS



- 5-15 GeV linac
- undulator fundamental: 0.15-1.5 nm
- $\varepsilon_x = \varepsilon_x =$ ~0.05 nm-rad
- peak brightness = 10^{33} ,pk power = 10s GW
- avg. brightness = 3 x 10^{22}
- photons/1 nC pulse =10^{12}
- pulse length < 230 fs
- rep rate = 120 Hz
- warm linac
- 100-m undulator, 5-mm gap

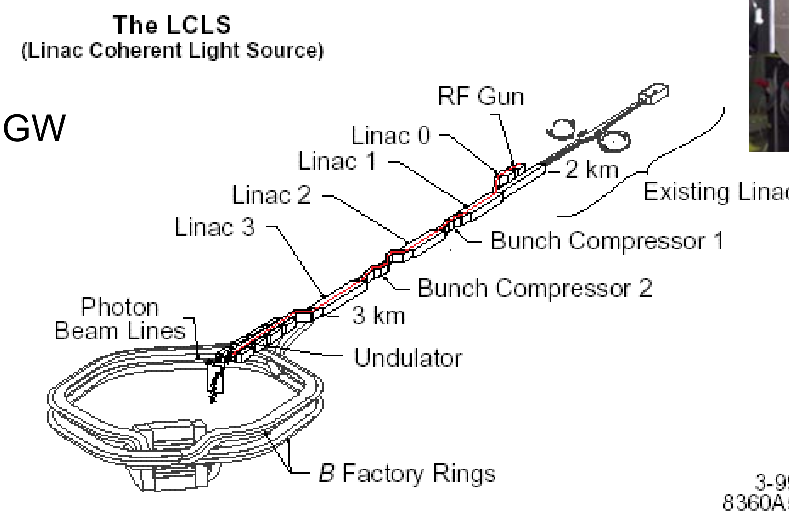
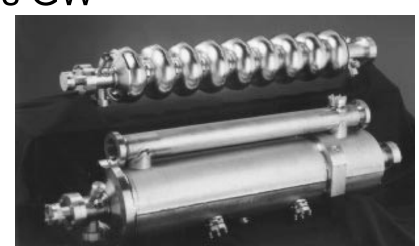


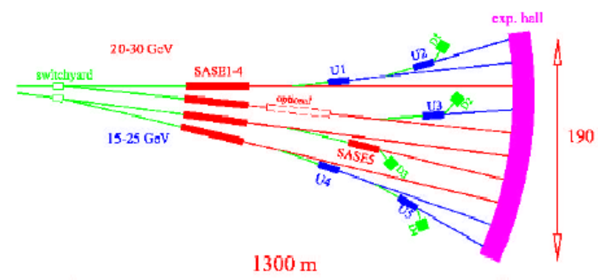
Figure 1. Layout of the Linac Coherent Light Source.

TESLA

- 15-30 GeV linac
- undulator fundamental: 0.1-6 nm
- $\varepsilon_x = \varepsilon_x =$ ~1 nm-rad
- peak brightness = 10^{33} , pk power = 10s GW
- avg. brightness = 3 x 10^{25}
- 11500 bunches, 1nC/bunch
- pulse length ~ 200 fs
- rep rate = 10 Hz
- superconducting linac
- 10 undulators, up to 323 m

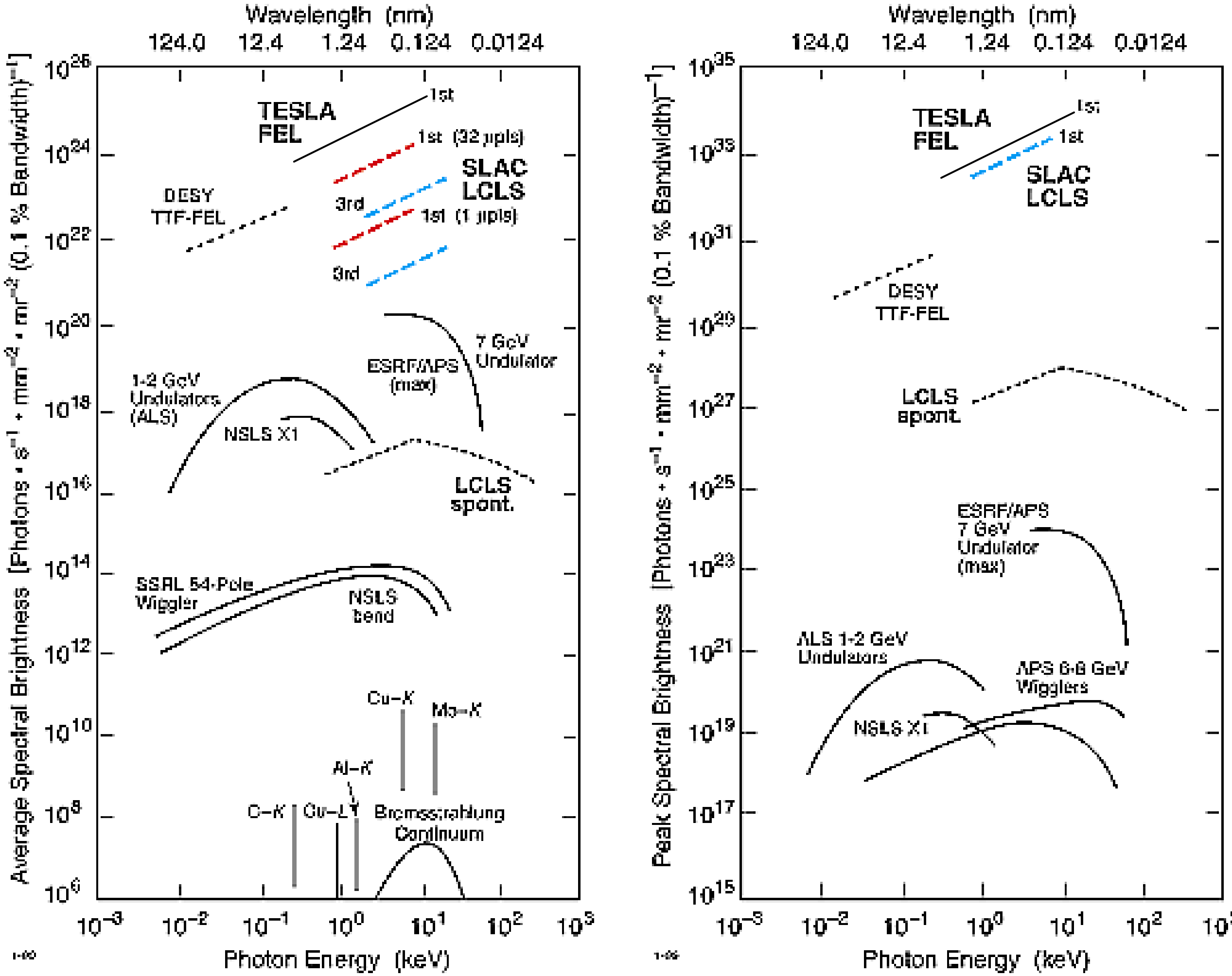


TESLA 1.3 GHz superconducting linac section



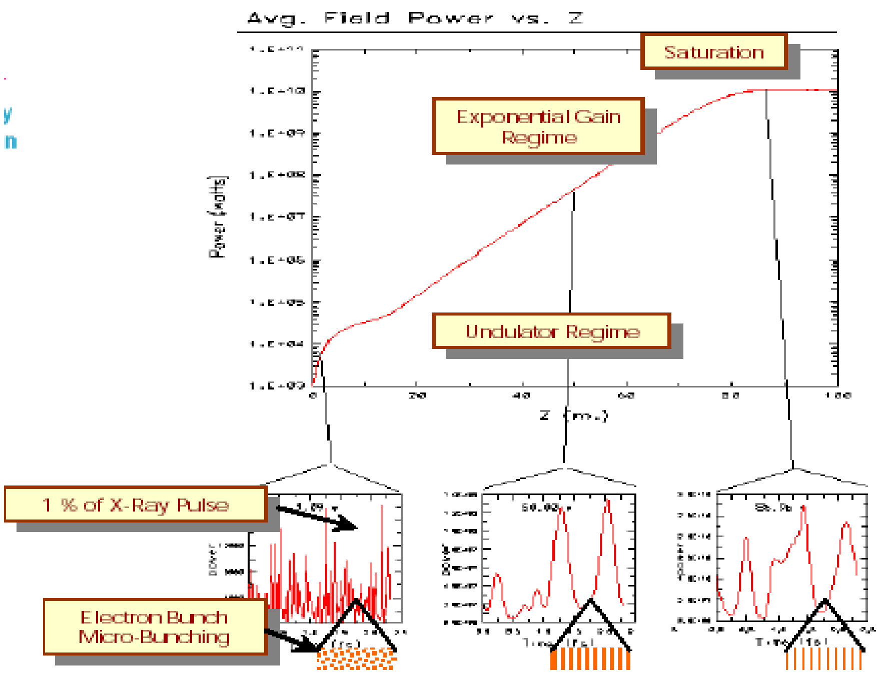
TESLA FELs

X-ray Linac FELs – cont.



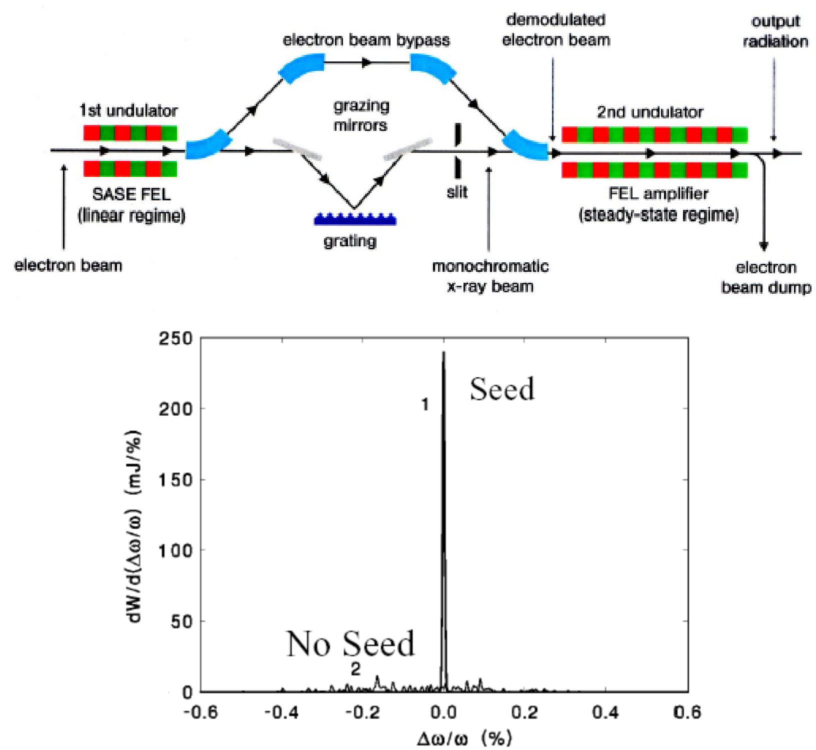
Linac FELs – SASE vs. Seeding

SASE
(start-up from noise)



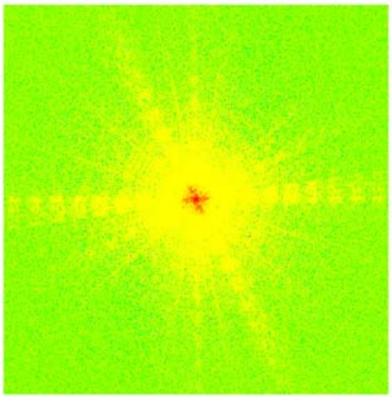
from K.-J Kim, 26th ICFA Beam Dynamics Workshop on Nanometer Colliding Beams

Self-seeded



seeding also reduces shot-shot intensity variations

Linac FELs – Coherence

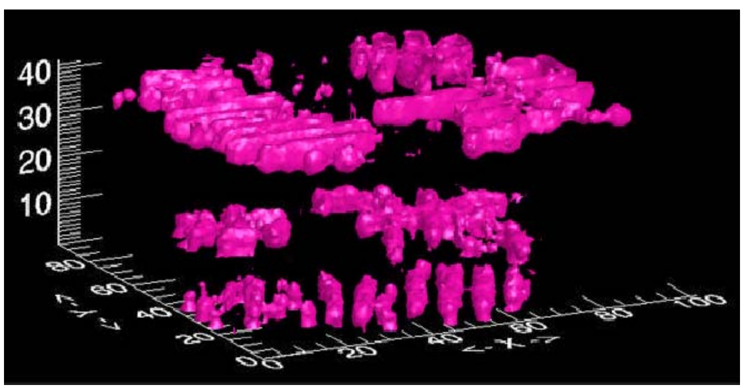


Miao *et al. PRL* (2002)

Coherent Scattering Pattern

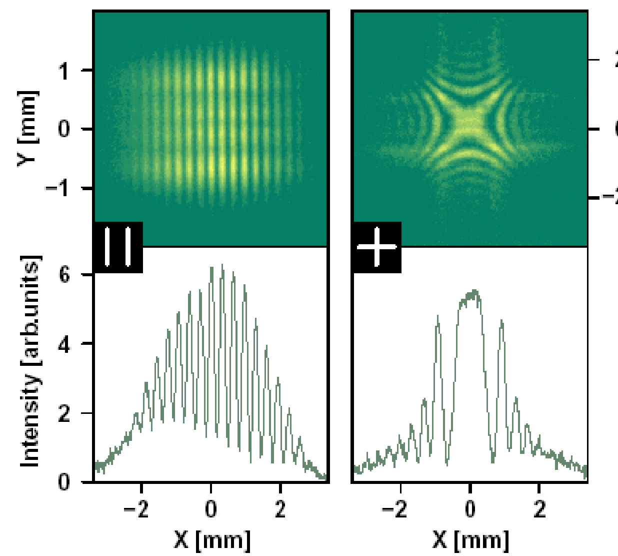
3rd Generation Beam Line	LCLS Source

Coherence Volume $1x5x50\ \mu m^3$	Coherence Volume $0.1x100x100\ \mu m^3$
Contains < 1 Photon	Contains 10^9 Photons



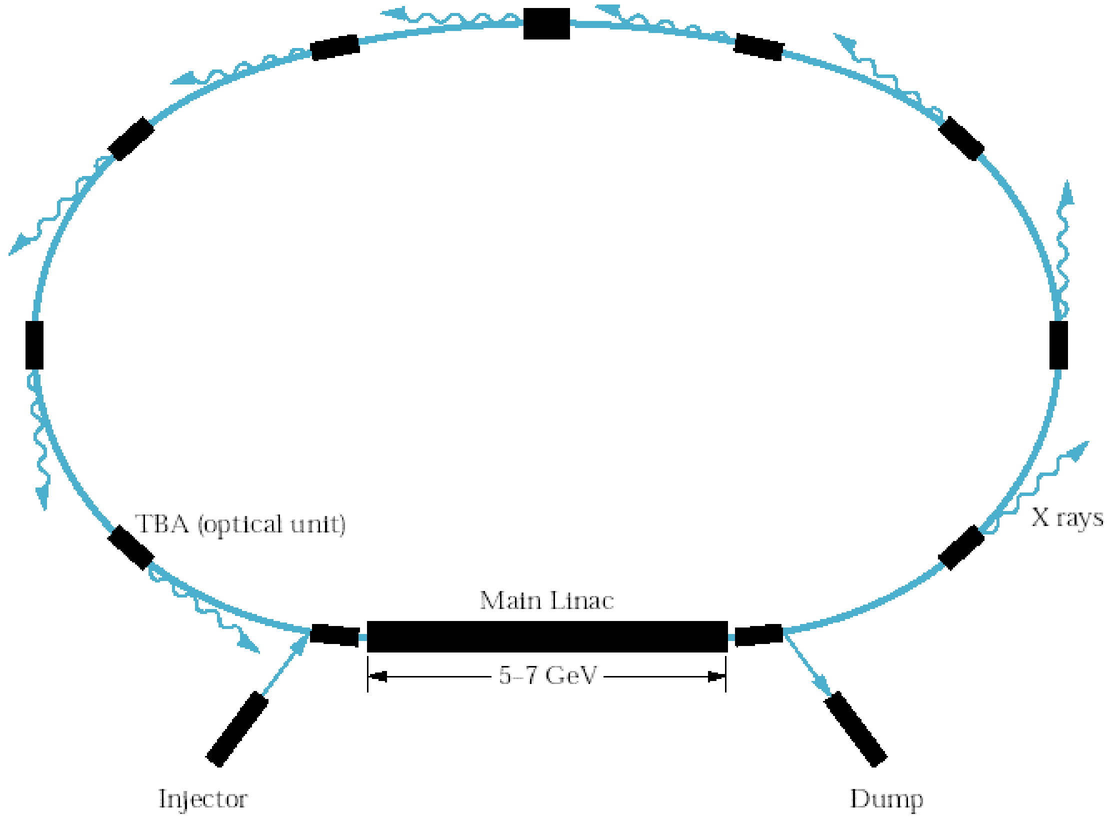
3D Reconstructed Image (~50 nm resolution)

after double slit after cross



from K.-J Kim, 26th ICFA Beam Dynamics Workshop on Nanometer Colliding Beams

Energy Recovery Linacs



S. Gruner, D. Bilderback, SLAC Beamline, Summer 2002

4^{th} Generation Light Sources – cont.

Energy Recovery Linacs (ERLs) – cont.

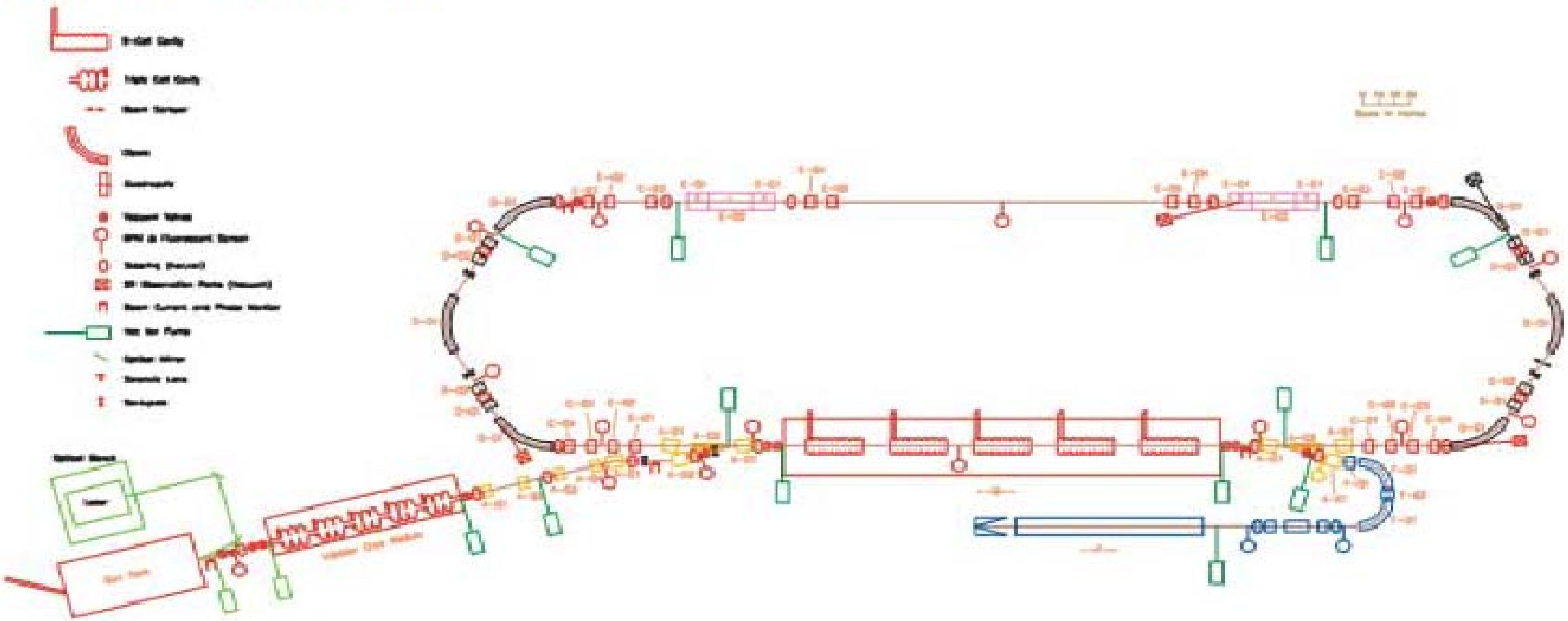
- Why energy recovery?
  - power to accelerate 100 mA to 3 GeV in 1 pass of linac:
    P = 0.1 A x 3 GeV = 300 MW
  - energy recovery is ~99.9% efficient
    $\Rightarrow$ ~ 300 kW for 100 mA, 3 GeV
    Q of rf cavities must be ~10^{10} $\Rightarrow$superconducting cavities
- Advantages:
  - transverse emittance ~0.1 nm-rad for multi-GeV, round beam
    preserves injector emittance (almost)
  - bunch length ~0.1 fs
    preserves compressed bunch length of injector
  - high rep rate
  - many beam lines
- Disadvantages:
  - low bunch current (advantage of short bunches diminished)
  - stability!

ERL Prototype

CORNELL
UNIVERSITY

We plan to begin work in the fall!

3.5 year construction, 1.5 year measurements



Beam Energy	100 MeV	Charge per bunch	77 pC
Injection Energy	5 MeV	Emittance, norm.	2* μm
Beam current	100 mA	Shortest bunch length	100* fs

* rms values

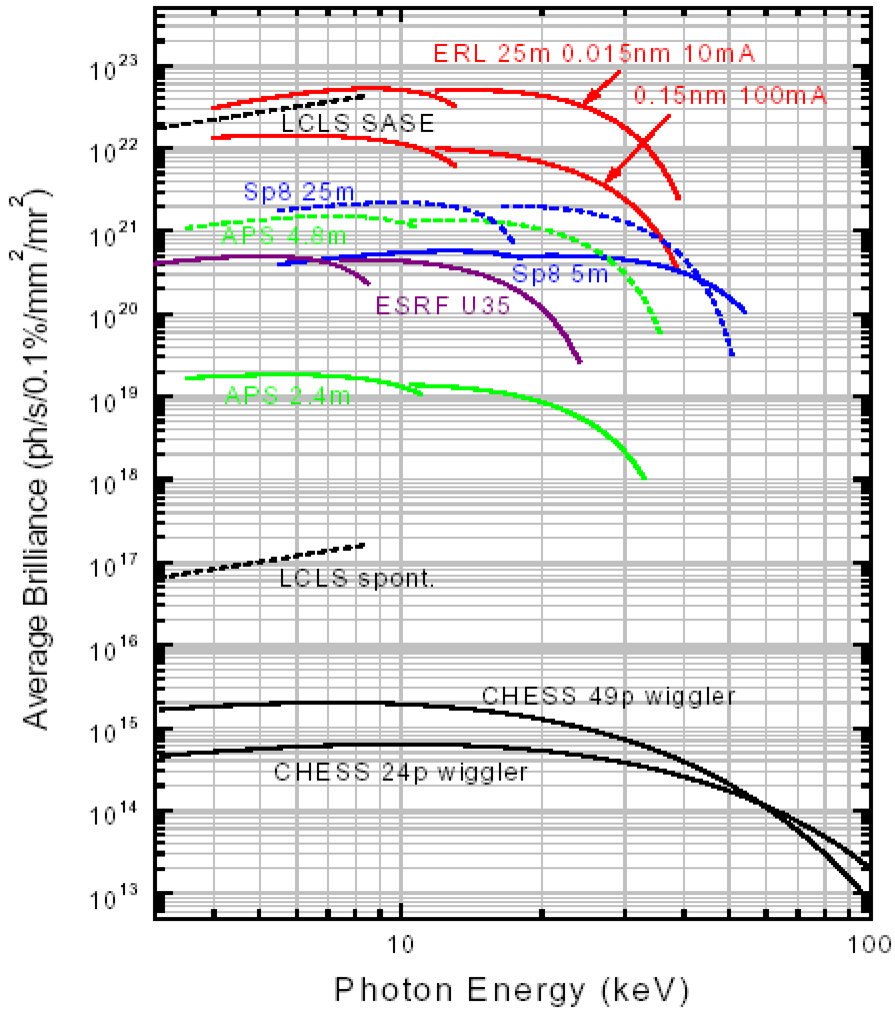
Jefferson Lab

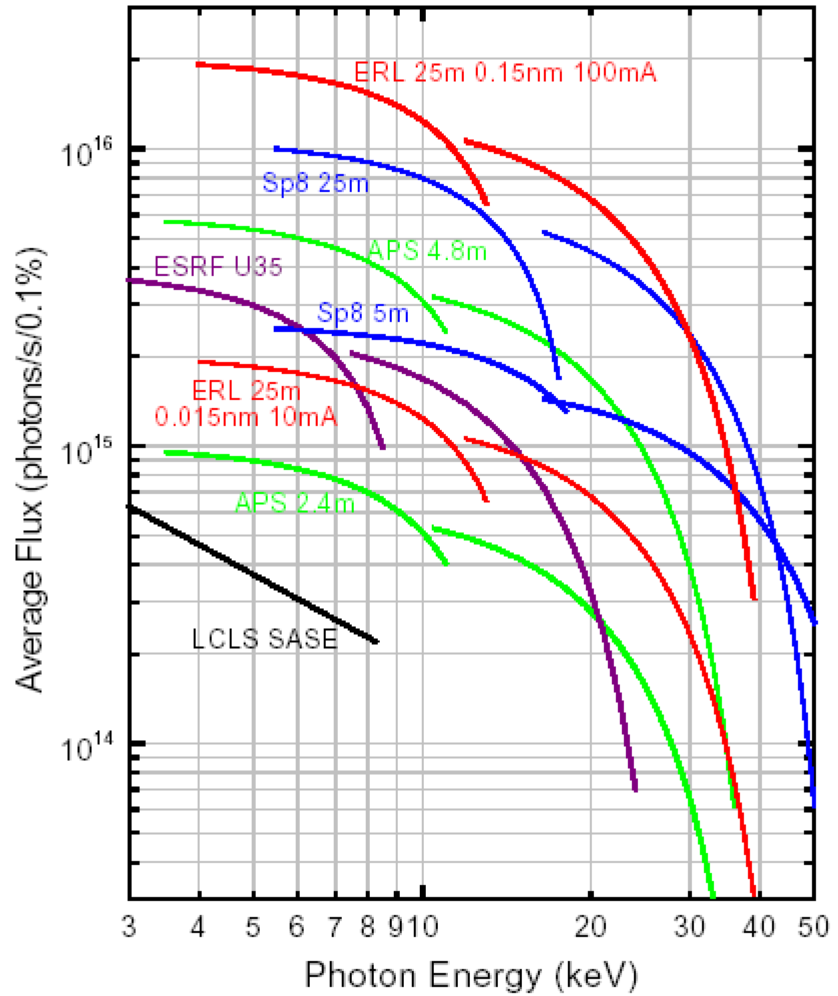
Recirculating Linac Light Sources

21 August 2001

ERL Performance

Q. Shen

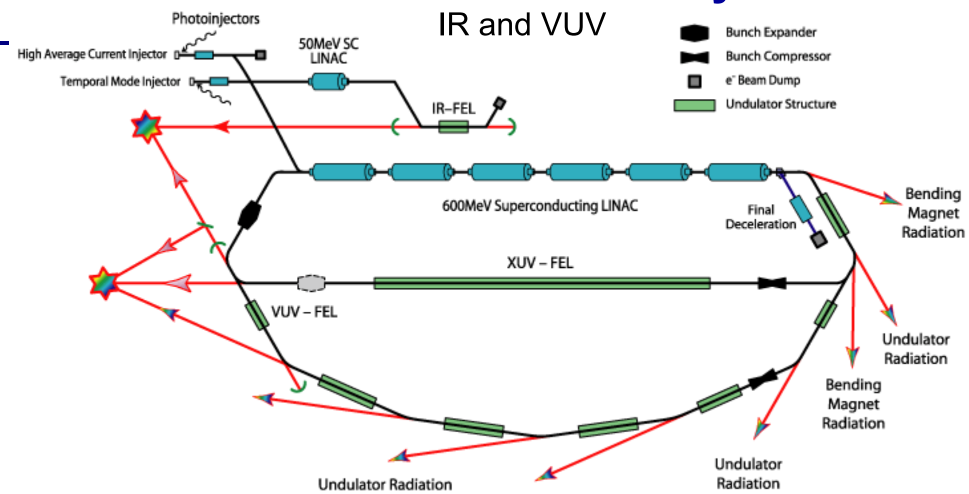




Energy Recovery Linac Plans

4GLS at Daresbury

IR and VUV



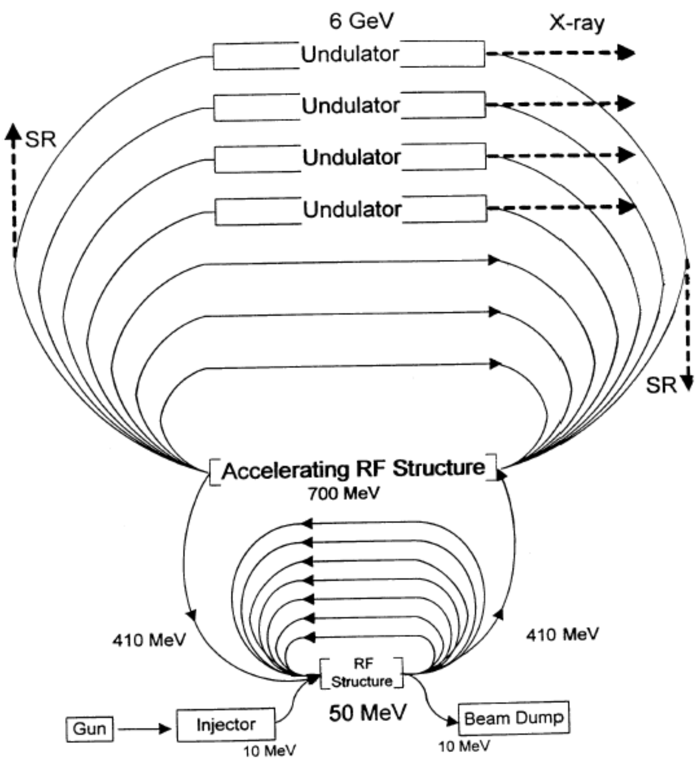
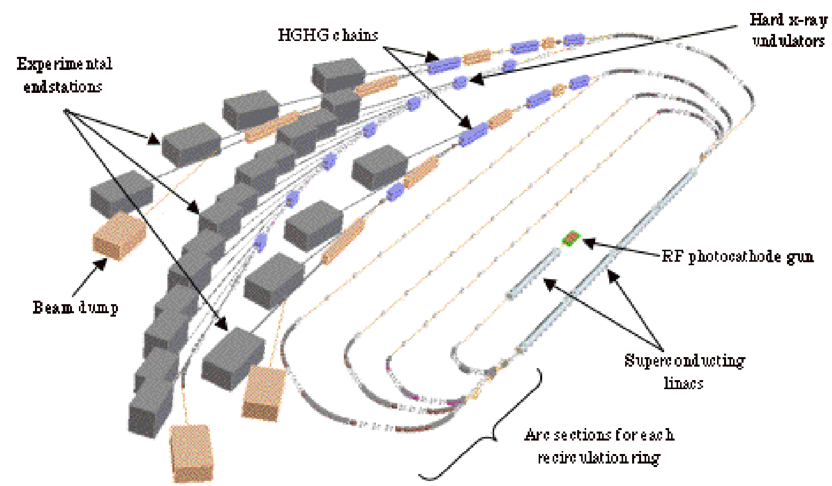


Fig. 1: Scheme of MARS.



MARS at BINP

G. Kulipanov, A. Skrinsky, N. Vinokurov

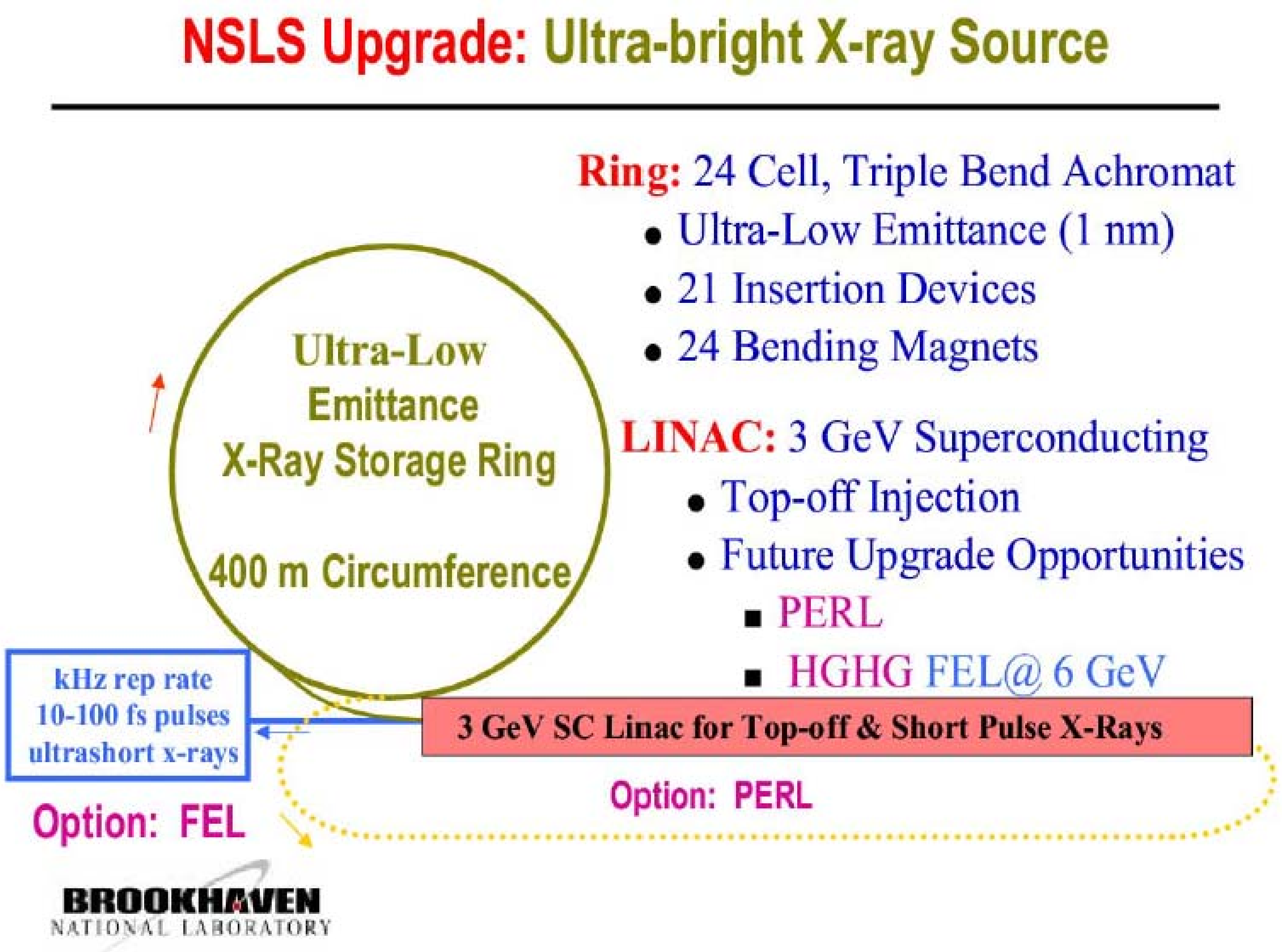
LUX at ALS

~3 GeV 50-100 fs by bunch tilting

HGHG seeded undulators

1 nC bunches @ 10 kHz

ERL + Storage Ring



4th Generation Source Comparison

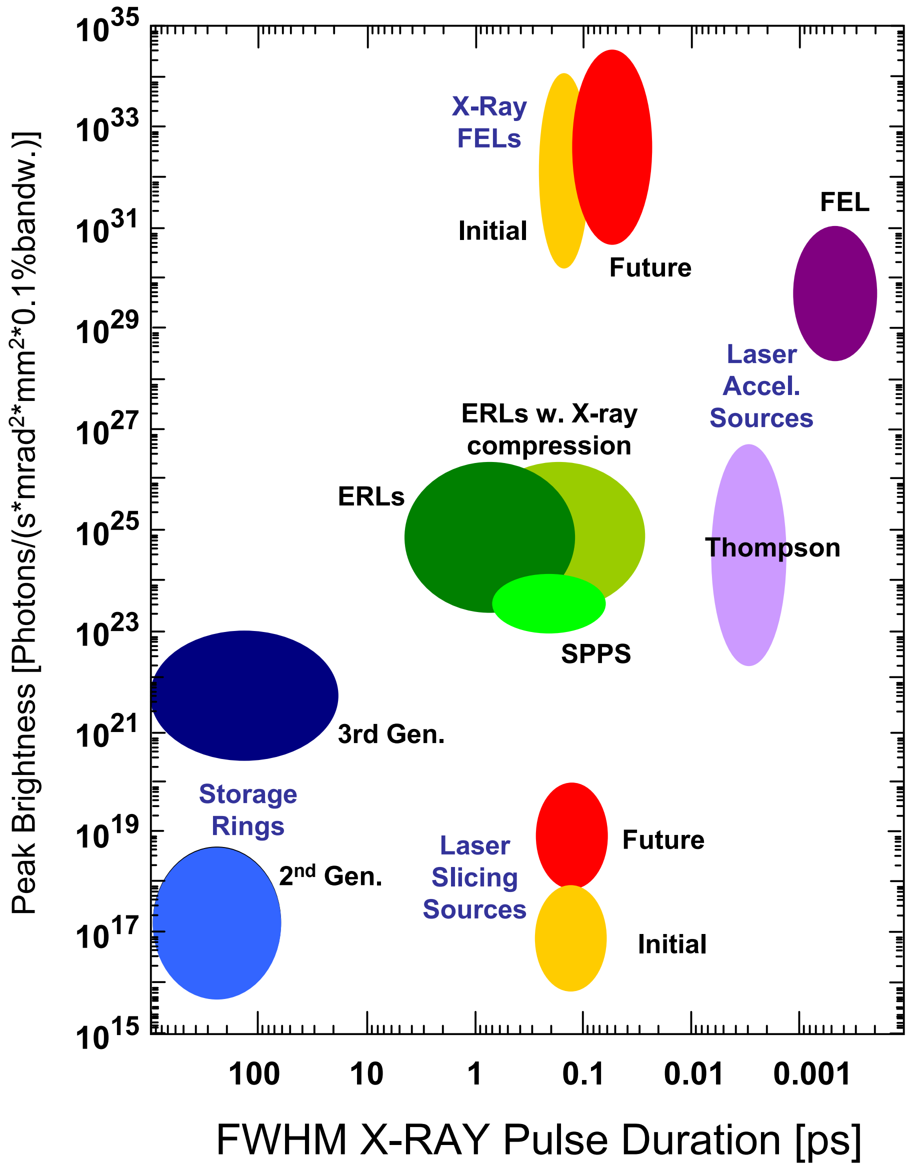
Flux and Brilliance

Comparison of flux and brilliance between the ESRF and some proposed sources including the UHXS storage ring source, the Cornell Energy Recovery Linac, and X-ray FEL sources based on Self-Amplified Spontaneous Emission (SASE). Part of the data in this table has been taken from the report "ERL_CHESS_memo_01_002.pdf" available from http//erl.chess.cornell.edu/ Papers/Papers.htm

Source Type	*ESRF Storage Ring*	*UHXS Storage Ring*	*Cornell ERL*	*LCLS SASE FEL*	*TESLA SASE FEL*
Electron Energy [GeV]	6	7	5.3	15	25
Average Current [mA]	200	500	100	7.20E-5	0.063
Hor. Emittance [nm]	4	0.2	0.15	0.05	0.02
Vert. Emittance [nm]	0.01	0.005	0.15	0.05	0.02
FWHM Bunch Length [ps]	35	13	0.3	0.23	0.09
Undulator Length [m]	5	7	25	100	200
Fundamental [keV]	8	12	8	10	12.4
Average Flux [Ph/s/.1%]	1.3E+15	2.0E+16	1.5E+16	2.4E+14	4.0E+17
Average Brilliance [Ph/s/.1%/mm^2/mrad^2]	3.1E+20	3.5E+22	1.3E+22	4.2E+22	8.0E+25
Peak Brilliance [Ph/s/.1%/mm^2/mrad^2]	3.3E+22	1.0E+25	3.0E+25	1.2E+33	7.0E+33

P. Elleaume, SLAC Beamline, Summer 2002

Brightness and Bunch Length of SR Sources



from H. Winick

Stability Requirement Preview

2nd and 3rd Generation Sources:

- orbit position < 1-5 μm
- orbit angle < 1-10 μrad
- beam size < 0.1 %
- e- energy < 5 x 10^{-5}

Improved 3rd and 4th Generation Sources:

- orbit position < 0.1-1 μm
- orbit angle < 0.05-0.5 μrad
- beam size < 0.01 %
- e- energy < 5 x 10^{-6}
- pump-probe timing synchronization for femtosecond sources < 100 fs